PROGRAMMABLE RECONFIGURABLE SELF-ASSEMBLY: APPROACHING THE PARALLEL HETEROGENEOUS INTEGRATION ON FLEXIBLE SUBSTRATES

Jae-Hoon Chung, Wei Zheng and Heiko O. Jacobs
Department of Electrical and Computer Engineering
University of Minnesota, Minneapolis, Minnesota, USA

ABSTRACT

This paper reports on a programmable reconfigurable liquid solder directed self-assembly (PRS) method to enable parallel heterogeneous integration of components on non-planar substrates. Metal contacts on segmented semiconductor devices bind to liquid-solder-based-receptors on a substrate surface during the fluidic self-assembly. Programmability is implemented using solder-based receptors that can be switched "ON" and "OFF" using integrated heaters. This programmability enables the heterogeneous batch integration of components by sequentially activating selected receptors. We fabricated a prototype substrate to experimentally test the feasibility of PRS and successfully demonstrate the programmable assembly of multiple types of components onto target positions.

1. INTRODUCTION

Fabrication strategies that rely on mechanisms of self-assembly are widely recognized as inevitable tools in nanotechnology. Self-assembly is not limited to the nanometer length scale. Strategies that are based on self-assembly are projected to have a major impact in the manufacturing of systems on both, the micro, and nanometer length scale[1, 2]. Previous demonstrations of a directed self-assembly to generate functional electrical microsystems include the coplanar integration of segmented integrated circuits (IC) using capillary forces [3], shape-directed fluidic methods to position electronic devices on planar surfaces [4], hydrophobic-hydrophilic surface directed self-assembly to integrate micro-optical components on silicon substrates [5], and liquid-solder directed self-assemblies to form functional two and three dimensional systems [6, 7]. In current self-assembly systems, all receptors are active during the assembly process. These systems allow the positioning of a large number of identical components onto planar and non-planar surfaces in a massively parallel manner. However, the adaptation of self-assembly to microelectronic systems, which consists of more than one repeating unit, is difficult to achieve due to insufficient power of recognition. For example, in shape-directed fluid self-assembly[4], small device components settle into the holes designed to match the shape of larger components; similarly, in surface tension driven self-assembly [7], the binding sites designed for one component will almost always find an overlap with the receptor for a different one. As a result the assembly of electrically functional heterogeneous systems that are built using non-identical components has not been possible. We and others are currently exploring the use of programmable sequential methods to overcome this limitations and to enable the formation of heterogeneous systems [8-11]. In this paper, we describe recent progress on a programmable reconfigurable liquid solder directed self-assembly (PRS) method [8] for the assembly of electrically functional heterogeneous systems. Our fluidic self-assembly process makes use of solder-based receptors that can be switched "ON" and "OFF" electrically. Metal contacts on the semiconductor device segments bind to activated liquid-solder-based-receptors on the substrate surface during the fluidic self-assembly process. The liquid-solder-coated areas provide three key requirements: they (i) act as receptors for subunits during the assembly (no manipulator is needed), (ii) they form rigid bonds upon solidification (no adhesive is needed), and (iii) they provide electrical input/output-connectors to operate the final device (no wirebonder is needed). Programmability is implemented using integrated heaters. The programmability enables the heterogeneous batch integration of components by sequentially activating selected receptor sites. The advantage of the assembly process over robotic assembly lines is that it is massively parallel — in each sequence thousands of components could be assembled at the same time — as a result the duration would not increase with the number of systems that need to be manufactured. In this report we present a feasibility study by estimating the required heating power to activate a receptor and the cross-talk between receptors with decreasing dimensions with and without liquid flow. Our theoretical calculations are confirmed experimentally by demonstrating the heterogeneous assembly of different semiconductor chips on flexible and curved substrates. The assembly of three non-identical semiconductor chips (GaAs, Si, GaP) with different dimensions ranging from (200 µm - 500 µm) has been accomplished. A total of 200 device segments have been assembled in three successive steps without defects.

2. METHODS

The basic principle of the liquid-solder-receptor-directed assembly process is illustrated in Figure 1. One side of the component is coated with a metal contact. This metal contact wets and binds to liquid-solder-based-receptors during the self-assembly process at a temperature where the solder is molten. The minimization of the free surface

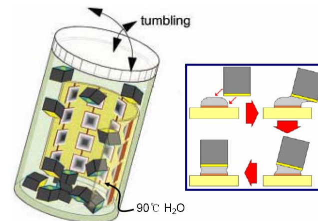


Figure 1: Surface tension directed self-assembly. The solder coated areas on the substrate wet and bind to the metal contacts on the device segments during the self-assembly process.

area of the liquid solder drives the assembly into a stable, aligned position.

The assembly of large number of identical components has been accomplished using this process - Figure 2 illustrates previous results where we assembled ~1500 silicon segments with the size of 300 µm onto a flexible surface [7] in 3 minutes.

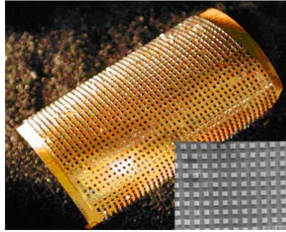


Figure 2: Batch transfer of 1500 silicon cubes onto a curved surface.

The basic concept of a parallel high-throughput heterogeneous self-assembly line is illustrated in Figure 3. This concept uses a well defined sequence instead of trying to assemble all components in a single step.

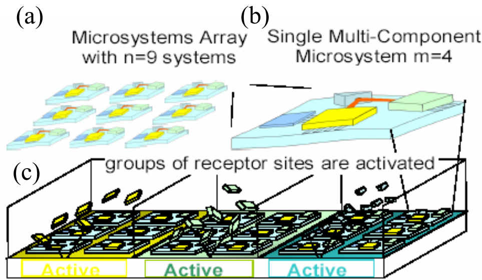


Figure 3: Concept of a "Sequential Self-assembly Manufacturing Line" to assemble multi-component micro-systems.

The illustration shows a 3x3 microsystem array (a), each of which contains four different components (b). The system is assembled by sequentially activating selected receptor sites (c). The activation of the receptors enables the programmable batch transfer of desired components onto desired locations. The concept to activate the selected receptor sites is illustrated in Figure 4. Our concept makes use of heaters that are integrated on the back side of a flexible substrate that supports the solder-coated areas. The self-assembly of the components occurs due to the reduction of the interfacial free energy. Components that are suspended in a solution that carry Cu-coated binding sites attach to solder coated areas that are heated above the melting point of the solder.

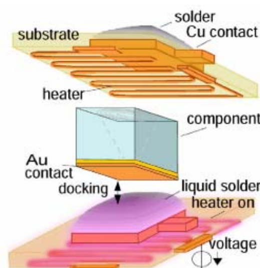


Figure 4: The solder sites are programmed by applying an external voltage to embedded heaters.

3. Simulations

To evaluate the feasibility of the proposed PRS concept, we performed computer simulations using ANSYS to estimate: (i) the necessary power to heat selected receptors to above the melting point of the solder, (ii) the minimal spacing between receptors for preventing thermal crosstalk, and (iii) the effect of the liquid flow in the agitated assembly solution. The substrate used for the simulation was a 20µm think-polyimide film with heaters on the backside. For the melting point of the solder we used 90 °C. The solder based receptor was considered to be activated "ON" in surface regions where the local temperature was larger 90 °C and considered to be non-active "OFF" in regions where the temperature was smaller 80 °C. The boundary condition of our simulation was a 10 mm wide, 10 mm deep and 10 mm tall channel with a fixed 20 °C temperature at the top. Without flow we used a fixed temperature (20 °C) boundary condition for the side walls. Under flow we used an incoming flow that had a temperature 20 °C at the flow rate of 0.1 m/s. Fig. 5 depicts the temperature profile with and without flow around differently sized receptors. The thermal coupling between receptors occurs through a 20 µm thick polyimide substrate, the liquid, and the liquid flow. Without flow the calculated heating power that was required to switch "ON" a receptor is typically in the µW regime: Receptors, 50 µm, 5 µm, and 0.5 µm in diameter that are surrounded with water require 480 µW, 50 µW, and 5 µW heating power, respectively. This linear relationship between the receptor size and power is interesting since the surface area reduces quadratically with size. However, this linear relationship is correct: Receptors with reduced dimensions produce an increased temperature gradient. The required power is proportional to the product of gradient and surface area, which becomes directly proportional to the size. The computer generated power levels are in good agreement with the analytically calculated power that is required to heat up a half sphere that is supported on thermally insulating film with no thermal losses to the substrate. The equations and results for the half sphere are summarized in Figure 6. Both the simulation and analytical first order estimates show that receptors can be closely spaced to each other. The maximum required spacing for a system with little or no liquid flow to maintain a 20 °C temperature drop is 20 µm, 5 µm, and 1 µm for 50 µm, 5 µm, and 0.5 µm sized receptors, respectively.

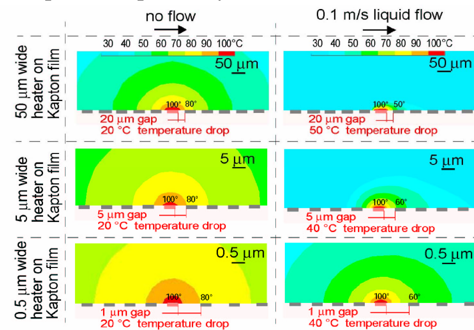


Figure 5: Temperature distributions around 50 µm, 5 µm and 0.5 µm wide heaters on a Kapton polyimide film with and without liquid flow.

The simulation also suggests that even higher integration might be possible in assembly systems that use a liquid flow for component transport and assembly. The required heating power, however, would go up.

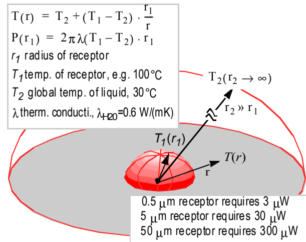


Figure 6: Temperature and power for a hemispherical receptor.

4. EXPERIMENTS AND DISCUSSIONS

We fabricated a prototype substrate to experimentally test the feasibility of PRS. The substrate has been fabricated using a polyimide film that has a copper cladding on both sides (Pyralux LF7022R, Dupont, Wilmington, DE). The polyimide film is appropriate to our application since it is very robust, flexible, thermally stable up to 350°C, and compatible with standard micro-fabrication processes. The fabrication process is illustrated in Figure 7. To facilitate the micro-fabrication process on the thin polyimide film, we attached the polyimide film onto a polydimethylsiloxane (PDMS)-coated silicon wafer. First, Shipley 1818 photoresist (Microposit, Phoenix, Arizona) was spin-coated on the backside of polyimide film at 3000 rpm for 30 sec and baked at 105°C for 2 minutes to protect the back during the processing of the fort side. Shipley 1813 photoresist (Microposit, Phoenix, Arizona) was spin-coated at 3000 rpm for 30 sec on the front of the substrate. After a soft bake at 105°C for 1 minute, the substrate was exposed to UV light through a dark field mask and developed in developer 1 MIF-351 : 5 H_2O for 15 seconds. The exposed copper area was etched by aqueous ferric chloride solution (1.4 g of $FeCl_3$ per milliliter of H_2O, pH 1.3). Shipley 1818 photoresist was spin-coated and cured to protect the patterned front side during the processing of the back side. We peeled off and remounted the polyimide film upside down on the PDMS coated silicon wafer. The same photolithography and etching sequence was used to fabricate the heater array.

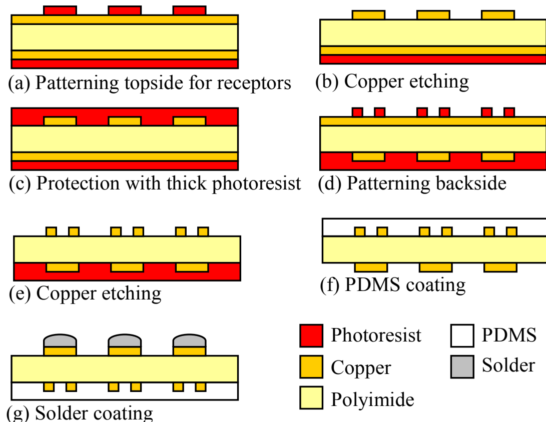


Figure 7: The fabrication process of substrate

PDMS was spin-coated on the heater side and cured in a convection oven for 1 hour. This PDMS layer was used as a thermal insulator for the heaters and as a mask to prevent solder wetting on the back side. Finally, the defined receptors were coated with solder by dipping the substrate into a liquid solder bath.

We tested the PRS with a meander type heater array. The self-assembly was performed in a small vial filled with DI water. The DI water was made slightly acidic (pH 2.5) with sulfuric acid to remove metal oxides from the surface of the solder and copper binding sites. We chose the solder (mp 47°C, LMA-117, Small Parts, Miami Lakes, Florida) which has been used in previous self-assembly experiment [7]. During the assembly process, we agitated the vial by hands until each activated receptor captured one component. We applied a voltage of 0.34V and a current of 0.87A to heat the three meander type heaters that were connected in series. We estimated the power to obtain a local temperature increase ΔT of 50°C using an equation for a hemi-cylindrical line type heater

$$P = \frac{\pi\, l \lambda \Delta T}{\ln(r_2 / r_1)}$$

[12]. We obtained 289 mW for our 150 μm wide (r_1 = 150 μm) and 15 mm long (l = 15 mm) heater that is located 2 mm away (r_2 = 2 mm) from the heat sink, which is in good agreement with the measured 296 mW.

The result of the sequential self-assembly process for three different components is illustrated in Figure 8. The total assembly process consisted of three sequential steps. In each assembly step, we added 300 components of a desired type in the assembly solution. Each self-assembly process took 3 minutes.

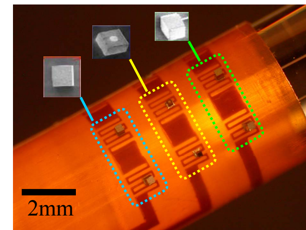
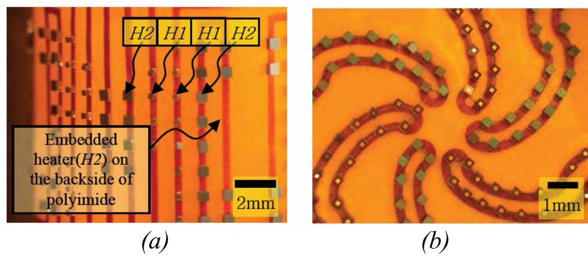


Figure 8 : Heterogeneous self-assembly programmed using meander type heaters.

To demonstrate the integration of components at a pitch that is twice the components size we used a linear copper metal layer as heaters -- 300 μm wide and 20 μm thick -- on the back side of the polyimide films. Figure 9(a) shows the assembly results of an *M*-shaped pattern that includes two different size silicon blocks (300 μm × 300 μm, 500 μm × 500 μm) that have been assembled on a curved surface. The 300 μm sized components self-assembled onto 300μm sized receptors with the heater *H1* being switched "ON", whereas the 500μm sized components self-assembled onto 500μm sized receptors with the heaters *H2* being switched "ON". Figure 9(b) shows 300 μm sized GaP-based light-emitting-diodes (LED) and silicon chips that have been assembled as programmed by the underlying heaters.



(a) *(b)*

Figure 9: Heterogeneous self-assembly programmed using linear heaters.

Our first attempts to assemble components at the illustrated density failed. We observed a higher thermal cross-talk between the lines than the expected thermal cross-talk. We were able to identified three reasons and eliminate the mismatch between our initial experimental results and the theoretical calculation. First, we did not provide an adequate heat sink to maintain a constant temperature profile. As a result we observed a steady temperature increase in our assembly solution that finally caused an activation of neighboring receptors. Second, the polyimide film was insufficiently thin to prevent thermal coupling through the glass wall of the vial. Finally, the melting point (mp 47°C) of our solder was smaller than what we used in our calculation. We succeeded to assemble the components at the illustrated density by: (i) immersing the vial in a cool water bath to provide an adequate heat sink, (ii) embedding a 1 mm thick PDMS thermal insulation layer between the polyimide film and the glass vial, and (iii) using a higher melting point solder (mp 138°C, LMA-281, Small Parts, Miami Lakes, Florida). To accommodate the high melting point solder we use an Ethylene Glycol solution (bp 197°C) instead of the water. The thermal conduction coefficient of Ethylene Glycol (0.25 W/m·°C) is 2.4 times smaller than the thermal conduction coefficient of water (0.6 W/m·°C), which further helps to reduce thermal coupling.

Throughout this study we found three types of defects: (i) empty receptors, (ii) receptor that captured two devices, and (iii) receptors that captured the wrong device due to thermal crosstalk. The first two defects that we observed were not inherent to the assembly process itself, but were caused by imperfections in both the receptors and the device segments. We were able to remove the first two types of defects by increasing the level of agitation [7] and by selecting components and materials that were free of manufacturing defects. We also succeeded to remove the last defects by maintaining a pitch that is at least twice the components size. We have not yet established the minimum size of components that can be assembled without defects, or the ultimate level of perfection that can be achieved as function of assembly time and component density.

5. CONCLUSIONS

We have proposed and tested a self-assembly process that could enable the massive heterogeneous integration of components on planar or non-planar surfaces. While the feasibility has been confirmed the technology remains in its infancies. For it to become useful the ultimate resolution limit, component density, and throughput need to be explored. Nonetheless, we believe that the outlined method has a number of advantages over existing self-assembly concepts. Once fully developed, it could be used to assemble almost any heterogeneous system that requires electrical interconnects. The self-assembly also becomes reconfigurable, i.e. the user can make changes by changing the location of activated receptors without fabricating a new receptor array. For example a matrix array could be used to program any desired configuration. The concept could also be combined with other sequential self-assembly methods that form three-dimensionally shaped microsystems [10].

6. REFERENCES

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