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OPTIMUM NUMBER DENSITY OF BLOCKS RELEASED IN FLUIDIC SELF-ASSEMBLY OF MICROELECTRONICS

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ABSTRACT

An experimental study was conducted to demonstrate the existence and estimate the value of an optimum number density of silicon plates (blocks) in a fluidic self-assembly process used for parallel assembling of microelectronics. Blocks ranging in size from 350 to 1050 microns were released under water over an inclined substrate and allowed to move gravitationally to fill indentations (receptors) of matching shape. The performance of the process was evaluated in terms of the time necessary to achieve filling. Results indicate that there is an optimum block density for which the filling time is minimum. If the density is too high, blocks in contact with each other form agglomerations that reduce the mobility of individual blocks and prevent them from aligning properly with the receptors to fill them. The optimum area fraction covered by blocks was relatively similar for the three sizes of blocks considered. The findings amend a common belief that the FSA performance increases indefinitely with the density of blocks released. Economic advantages of a limited block density at industrial scale are discussed.

INTRODUCTION

Developments in micro-electro-mechanical systems (MEMS) indicate the existence of two technological directions for assembling electronic components: serial and parallel methods [1]. The pick-and-place has been traditionally used as a serial method for assembling electronic components. The method requires the use of micro-grippers and high precision, robotized actuators. The productivity is relatively reduced as components are mounted one at a time. Use of pick-and place is particularly difficult in the sub-millimeter size where adhesion and electrostatic interactions between the gripper and electronics to be assembled become dominant over gravity.

The parallel approach is a better choice for assembling large numbers of small components. Two classes of parallel methods are known [1]. The first is called deterministic and involves transfer of microstructures between two aligned wafers. The second class, represented by self-assembly, is called stochastic due to the initially non-organized nature of the mass of components to be assembled. The driving force is a key characteristic of the latter category. Several techniques have been described in the literature. Assembly attempts were made by using the electric field to drive small LED devices to selected sites for positioning [2]. Surface tension and gravity were used to assemble separated parts into structures based on the weak attractive forces given by modifications of menisci around bodies [3]. Hydrophobic vs. hydrophilic characteristics and fluidic agitation have been explored in assembling millimeter-size hexagonal rod-shaped components into arrays [4]. Research was performed on self-assembly of micro machined silicon parts onto silicon and quartz substrates, based on shape recognition and interfacial energy minimization [5].

Fluidic self-assembly (FSA) consists of the motion of a large number of parts (blocks) over an inclined substrate and their seating in previously created indentations of matching shape (receptors). The process, developed in the last few years, is attractive because of its simplicity and natural occurrence of assembling events [6]. However, it is characterized by complex fluid and solid dynamics phenomena at scales as small as micron range. The FSA outcome depends on complex block-substrate-fluid interactions and process parameters. Developing a theoretical model that accounts for all of the above factors is a difficult undertaking. A more practical approach is to identify the most influential factors and optimize FSA with respect to those factors. Although the number density of blocks released over the substrate is such an influential factor, no systematic study has been reported to quantify its importance on process performance. The authors' interactions with specialists involved in FSA development point to a common belief within the FSA community that process performance increases indefinitely with the number density of blocks released. As a result, only high block densities have been used in FSA experiments so far.

Research Hypothesis

Fluidic self-assembly is a stochastic method based on the large number theory. If a sufficient number of blocks move by a given receptor, one block will eventually have the proper orientation to fill the receptor. It has been stated in literature [6] that the filling rate is a function of number of blocks passing by a hole and the probability that each individual block will fall into the hole. From preliminary observations on numerous FSA experiments, the two probability factors have opposite variations with block density, as shown qualitatively in Figure 1. Curve A represents the number of blocks passing by a hole, which, for a fixed experiment time, increases proportionally with the block density. However, if the blocks become too numerous, they form agglomerates within which individual blocks lack the mobility necessary to align with the receptors. The probability of an individual block to fill the receptors is accordingly lower (curve B). It was hypothesized that there exists an optimum density as a compromise between the two factors where the process performance (curve C) is maximum. The present paper describes the experimental program aimed at validating the above hypothesis and estimating the optimum parameters.

METHODS

Fluidic self-assembly was performed on polysulphone substrates with predefined indentations (receptors) produced by hot press embossing. The receptors were in the shape of 65-micron thick truncated pyramids with square base, the larger base up and the side surfaces tapered by 47 degrees from the vertical. Three different block sizes were used with the larger base of 350, 850, and 1050 microns. Different arrangements of the receptor holes were used for the three sizes as shown in Figure 2 (receptor contours in Figure 2a were digitally enhanced for better visualization). The substrate was mounted on a plane chuck whose angle from horizontal could be finely adjusted. To break adhesion forces and promote block motion along the substrate, the chuck was externally vibrated using a piezo-electric actuator. The silicon blocks had a shape matching that of the receptors, with the larger base being 0 to 5 microns shorter than the receptor's to facilitate self-assembly. A color video camera (Sony DXC-190) equipped with a performance lens (Hirox HRX-CX-5040RZ-FCLS) was used to capture top view footage of the blocks as they moved across the substrate. The lens magnification was set between 20X and 50X, function of the block size. The resulting field of view for 350, 850, and 1050-micron blocks was 0.4, 0.95, and 1.13 cm^2, respectively. Blocks were released for fluidic self-assembly from a distance of 5-7 cm above the substrate using a pipette. The inclination angle of the substrate was between 12 and 16 degrees. This parameter was selected based on preliminary tests, which indicated that for smaller angles the blocks did not move consistently, while for larger angles their speed was too high for FSA. The vibration frequency was between 170 and 230 Hz. Experiments were conducted under de-ionized water, with zonyl used as a surface tension reducer to ease block movement over the substrate.

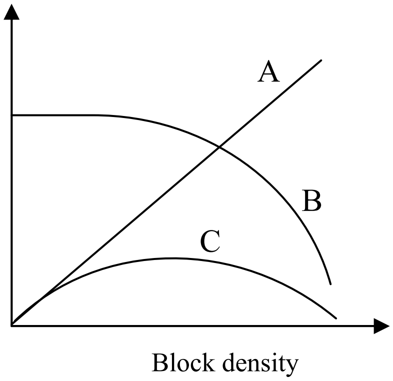


Figure 1 Qualitative representation of number of blocks passing by a receptor (A), probability to fill the receptor (B), and overall FSA performance (C) in terms of block density.

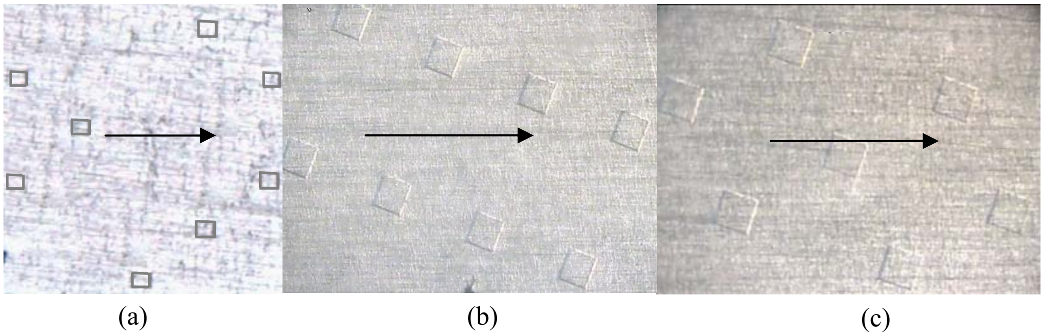


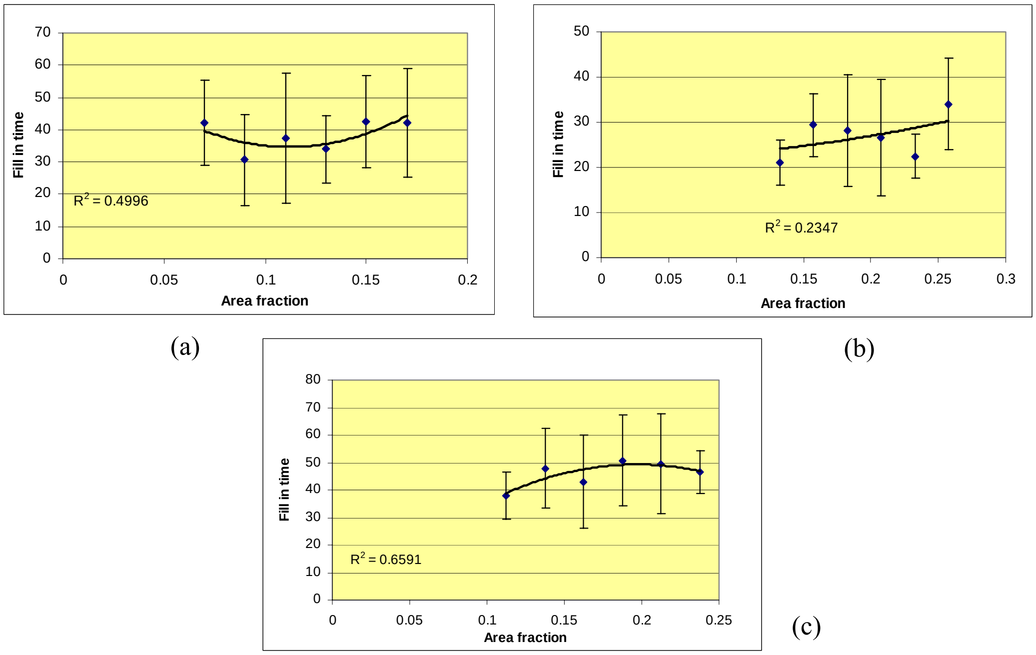
Figure 2 Receptor site configurations: (a) 350-μm size receptors. (b) 850-μm size receptors. (c) 1050-μm size receptors. Block movement direction is indicated by arrows.

The density of blocks was defined as the average number of parts per unit area and was chosen to be the main input parameter for the experiments. The methodology of evaluating the density consisted in on-screen counting of blocks. Counting was done every two to four seconds based on video recording duration and the average density was calculated for the entire experiment as the mean density over all frames. The density was then converted to the area fraction of substrate covered by blocks using the field of view and the area covered by one block. The experiment was stopped when (a) the last receptor seen in the field of view was filled, or (b) when agglomerations of interlocked blocks became stationary around one or more receptors preventing other blocks from approaching the receptor. The latter situation was not frequent and occurred typically when only one or two receptors were left unfilled. Because density could not be accurately controlled from the release phase, a large number of FSA runs were carried out and the results were then classified based on the area fraction defined above. Over 100 experiments were performed for each block size, summing up to a total of 350 experiments. The filling time was measured as the main outcome parameter, with shorter times representing better process performance.

RESULTS AND DISCUSSION

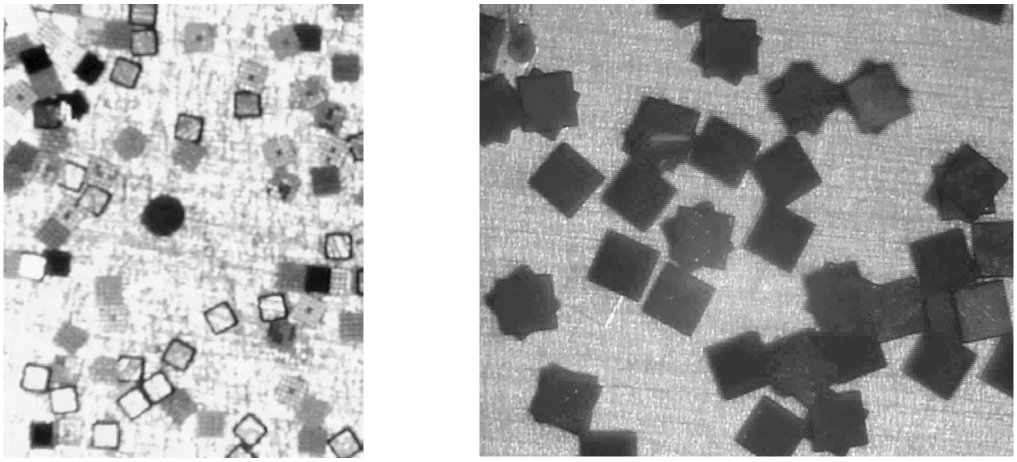
The filling time is shown in Figure 3 as a function of the area fraction covered by blocks for the three different block sizes. To generate the graphs in Figure 1, data for individual tests were divided into 6 bins of equal width. The mean filling time for all the tests in a bin is plotted, along with the standard deviation. A parabolic curve was fitted through the mean values. The resulting correlation coefficients are between 0.23 and 0.66. This is indicative of relatively weak trends, which was expected given the variability of the stochastic FSA process. For 350-micron blocks (Figure 3a), a minimum time was identified at an area fraction between 0.11 and 0.12. For 850-micron blocks (Figure 3b), a minimum could not be found in the range of area fraction covered by experiments, but the trend shows an increase in filling time with the block density. The shortest filling time was recorded for an area fraction of approximately 0.13. In the case of 1050-micron blocks (Figure 3c), an increasing trend was again observed, except for the largest area fraction covered, where the filling time had a slight drop. The area fraction corresponding to the shortest filling time was found at approximately 0.11, very close to the other cases.

The behavior of the blocks moving across the substrate was analyzed to explain some of the above quantitative results. Figure 4 contains frames where the blocks of 350 microns (Figure 4a) and 1050 microns (Figure 4b) have a relatively uniform distribution, typical to the moderate average density values. The direction of motion is from left to right. There is sufficient spacing between blocks so the blocks have the necessary mobility to rotate and align with the receptors. The negative effect of excessively large block densities can be seen in Figure 5. Clusters of interlocked blocks (shown inside black line



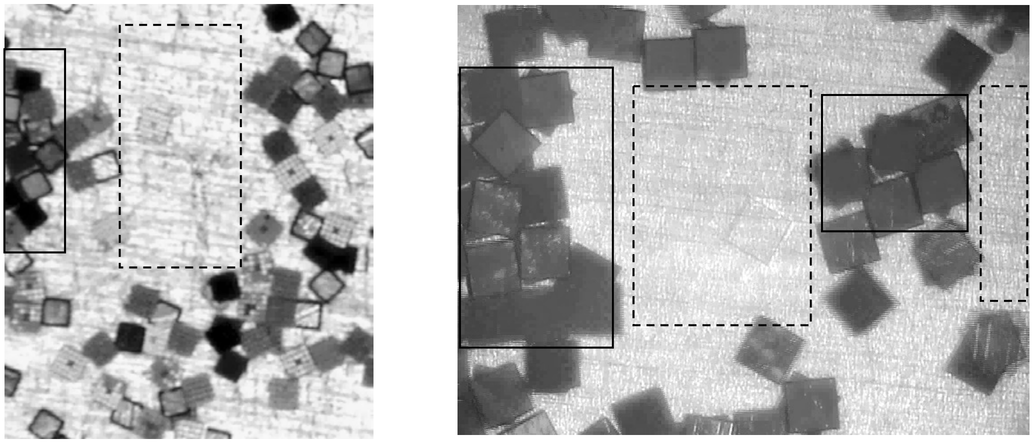
(a) (b) (c)

Figure 3 Filling time as a function of block density for (a) 350-micron, (b) 850-micron, and (c) 1050-micron blocks.



(a) (b)

Figure 4 Frames captured from FSA experiments where the block distribution on the substrate was relatively uniform: (a) 350-micron blocks; (b) 1050-micron blocks. Block movement was from left to right.



(a) (b)

Figure 5 Frames captured during FSA experiments where clustered blocks (inside solid line rectangles) had less mobility and prevented other blocks from reaching the regions ahead (dashed line rectangles): (a) 350-micron blocks (b) 1050-micron blocks. Block movement was from left to right.

rectangles) were temporarily formed, that moved down the substrate like large solid bodies. Blocks within these agglomerations did not have the rotational mobility necessary to fill the receptors. In addition, if a block at the leading edge of a cluster became immobilized by adhesion forces or by an incorrectly filled receptor, the whole cluster stopped moving. As a result, the region ahead of the cluster was not accessible to other blocks and became devoid (see white rectangular areas). This extended the filling time, reducing the FSA performance.

It should be noted from Figures 4 and 5 that the higher aspect ratio 1050-micron blocks had a considerable tendency to stack up when the large bases of two blocks came in mutual contact during the dispensing stage. This problem could be avoided by adding features such as bumps to the larger base of the blocks, or make its surface rougher. Also, use of a dispensing method where the blocks are shaken to prevent them from adhering to each other would reduce stacking.

CONCLUSIONS

There exists a common belief among the FSA community that the process efficiency improves indefinitely with the density of blocks dispensed. In contrast, this study suggests that the best performance is obtained when the block density is limited about an optimum value, and higher densities cause a drop in performance. This verifies the hypothesis stated in relation to Figure 1. As the number density of blocks released was increased (curve A), more blocks moved over each receptor and the number of opportunities for a filling event was higher. However, the probability for each block to fill a receptor (curve B) depends on the ability of the block to rotate and align with the receptor. This probability was experimentally observed to decrease with an increase in block density due to the reduced rotational mobility of blocks when they were part of large clusters. As a result, the fill-in time, used as a measure of the overall FSA performance (curve C) reached a minimum around block densities corresponding to area fractions of 10-15%.

Applied to an industrial FSA process, this result provides the additional economic advantage of dispensing fewer blocks overall to produce the same electronic circuits, therefore lower production costs.

Qualitative analysis of the footage recorded in FSA experiments allowed identifying mechanisms that hinder the attainment of maximum process efficiency and directions for improvement. Such improvements include different block geometry, surface features, and a better dispersion from the dispensing stage.

The stochastic character of FSA leads naturally to a large variability in the process output parameters. Relatively low correlation coefficients, indicative of weak, sometimes subtle trends, are therefore expected. In addition, numerical results depend on the materials, fluid, surface quality, and other conditions specific to the process. In light of the above arguments, caution must be exerted when applying in practice the quantitative findings of this study. However, the existence of an optimum block density is an important qualitative result, based on which optimum process conditions can be determined experimentally for any given industrial FSA.

ACKNOWLEDGMENTS

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