An Automated Stage for Scalable Imprinting of DNA Nanowires Based on a Self-Aligning Technique

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AN AUTOMATED STAGE FOR SCALABLE IMPRINTING OF DNA NANOWIRES
BASED ON A SELF-ALIGNING TECHNIQUE

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ABSTRACT

Molecular combing is an established technique for aligning DNA nanowires on a surface. When performed on micro-patterned surfaces, this technique can be used to reliably align and stretch DNA nanowires across micro pillars. Imprinting of these aligned DNA nanowires is an affordable technique for fabrication of arrays of nano-scale channels across micro-scale reservoirs. In the past, DNA combing and imprinting (DCI) have been performed manually to fabricate polymer chips that are used in biomedical applications such as gene therapy and drug delivery studies. Automation of the DCI process is necessary to improve the yield and to scale-up production for these applications. However, existing automated techniques are not appropriate for DNA nanowire imprinting because these techniques cannot handle (i) fragile stamps and (ii) individual chip scale stamps of size ~1 cm². Herein, we present the design, fabrication and performance evaluation of an imprinting stage that enables (i) handling fragile stamps via low-cost equipment and (ii) production scale-up via simultaneous handling of multiple stamps. The stage is based on a self-aligning imprinting technique that passively aligns a stamp parallel to the substrate thereby enabling simultaneous imprinting of multiple stamps. The stage is designed on a single stage. This self-alignment technique minimizes nanowire breakage by ensuring (i) minimal in-plane stamp motion during imprinting and (ii) that the contact forces do not exceed the weight of the stamp. Based on this technique, we have designed/fabricated a stage that can simultaneously handle three stamps and is capable of further scale-up. The stage consists of a movable platform that is mounted on linear bearings and is actuated via a stepper motor. Stamps are loaded onto a holder that is mounted on the movable platform via kinematic couplings. This allows one to rapidly attach and detach the holder from the stage and also makes it possible to handle fragile stamps during loading/unloading. Imprinting of DNA nanowires with a manual stage has demonstrated the feasibility of the self-alignment scheme. Experiments that were performed to test the alignment capability of the stage verify that conformal stamp contact can be achieved across all three stamps even in the presence of an angular misalignment of 5° between the stamp and the glass slide. This ability to simultaneously align multiple stamps is a critical step in being able to scale-up and fully automate the DCI process.

INTRODUCTION

The ability to reliably align large arrays of DNA nanowires via well-established laboratory techniques, such as molecular combing, opens up an economical route to fabricate nano scale patterns [1-3]. For example, arrays of DNA nanowires aligned across micro pillars on a soft elastomeric stamp may be used as a template to fabricate nano-channels via imprinting onto ultraviolet (UV) or thermal curing polymer [4]. Although manual alignment and imprinting is feasible, automation is necessary to improve the yield and to scale-up production. Existing automated techniques are unsuitable for DNA nanowire imprinting because of their inability to handle large volumes of chip scale and fragile stamps. Herein, we have developed a self-aligning imprinting stage that enables (i) imprinting of DNA nanowires via low cost equipment and (ii) production scale-up via simultaneous handling of multiple chip scale stamps.

DNA combing and imprinting (DCI) is a technique that has been recently developed for fabricating arrays of nano-channels across micro scale reservoirs [4]. These nano-channels are fabricated via pattern transfer from a micro patterned stamp that has DNA nanowires stretched across the micro features. A schematic of the process is shown in Fig. 1. The DCI process consists of two major steps: (i) molecular combing that aligns DNA nanowires across arrays of micro scale features on the stamp and (ii) imprinting these nanowires onto a suitable substrate such as a polymeric layer on top of a glass slide via
UV curing/flash imprinting. Additionally, an intermediate step of gold coating the stamps may be performed to tune the diameter of the nanowires. Finally, after imprinting, the gold coated DNA nanowires are etched away leaving behind nanochannels across micro scale reservoirs on the polymeric substrate. In the past, DCI has been performed manually to fabricate polymer chips that are used in biomedical applications such as for drug delivery studies [5].

Imprinting is the bottle-neck for automating and scaling-up the DCI process. Currently, imprinting during DCI is performed manually; this limits the yield of the process to about 20%. The process yield also depends heavily on the skill of the operator as imprinting involves handling stamps with fragile DNA nanowires. The role of automation is to (i) ensure a controlled and repeatable imprinting and (ii) provide material handling that is suitable for transporting fragile stamps.

The advantages and limitations of existing high-throughput automated imprinting schemes are summarized in Table 1. Existing imprinting techniques, such as nano-imprinting lithography [6] and roll-to-roll imprinting [7], are not appropriate for DCI automation. This is because these techniques cannot handle (i) fragile stamps and (ii) individual chip scale stamps of size ~1 cm². Although high-precision alignment stages are available for imprinting fragile stamps, the size of the DCI stamp places an additional constraint on scalability. For biomedical applications, it is more desirable to imprint individual chip scale stamps than to dice-up a large wafer into smaller chips after imprinting. Scale-up would then involve introducing a precision stage for each chip; this is not a practical solution scheme. We have solved this coupled problem (fragile stamps vs. scalability) by developing a self-aligning imprinting technique that enables simultaneous imprinting of multiple fragile stamps via a single stage.

Table 1: Comparison of existing imprinting techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantage</th>
<th>Limitation for DCI automation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano-imprint lithography</td>
<td>Scalable to large area wafers</td>
<td>High contact pressures (~10,000 times)</td>
</tr>
<tr>
<td>Roll-to-roll imprinting</td>
<td>High throughout continuous imprinting</td>
<td>Rolled-up stamp fabrication</td>
</tr>
<tr>
<td>Nano-positioning stages</td>
<td>Imprinting at low contact forces</td>
<td>Not easily scalable</td>
</tr>
</tbody>
</table>

DNA COMBINING AND IMPRINTING BACKGROUND

DNA combing and imprinting

The first step during DCI is similar to molecular combing that has become a standard technique for visualization of single DNA molecules [1-2]. The only difference is that combing is performed on a micro patterned stamp so that the DNA molecules are aligned and stretched across the micro pillars on the stamp. The imprinting step is similar to nano-imprint lithography [6] with a major difference that the nano scale features on the stamp are made up of fragile DNA nanowires instead of the stamp material itself. These nanowires may break during imprinting due to high contact forces. Thus, imprinting yield is dependent on the ability to perform imprinting under low contact forces. As contact forces depend on the technique used for aligning the stamps parallel to the glass substrate, alignment is critical to improving the DCI process yield. Herein, we have developed and implemented a self-aligning technique that ensures that the contact forces don’t exceed the weight of the stamp and thereby reduces defects.

Imprinting process and functional requirements

The steps of the imprinting process are: (i) unloading the stamp from the gold evaporation chamber and surface treating the stamps, (ii) loading the stamp and the glass slide onto the stage, (iii) aligning the stamp and the glass slide parallel to each other, (iii) making conformal contact between the stamp and the glass slide, (iv) dispensing UV curable monomer solution into...
the contact zone between the stamp and the glass slide, (v) curing of the dispensed monomer solution via UV polymerization, and (vi) detachment and removal of the stamp from the glass slide.

The key step during imprinting is to align the stamp and the glass slide parallel to each other without damaging the fragile nanowires on the stamp. This alignment is critical to producing conformal contact between the stamp and the glass slide, which ensures proper dispensing, distribution, and curing of the monomer solution; all these factors are vital for the production of high quality chips. Also, in-plane motion is another major concern during imprinting. Throughout the stage travel, it is crucial that the stamp and glass slide do not slip in-plane with respect to each other during alignment. Once the stamp and slide make their initial contact, the remainder of the travel must be such that it minimizes the dragging of the stamp with respect to the slide. Friction forces between the two surfaces can damage the delicate DNA strands and reduce the yield of the process. Consequently, it is important that any imprinting scheme minimize this in-plane motion as much as possible. The functional requirements for the stage are listed in Table 2. Herein, we focus only on the parallelism alignment between the stamp and the glass slide as in-plane alignment/registration is not essential for improving the imprinting yield.

<table>
<thead>
<tr>
<th>Physical constraints</th>
<th>Functional requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of stamp: 10 mm×10 mm×3.25 mm</td>
<td>Critical alignment directions: out-of-plane (tip, tilt and z)</td>
</tr>
<tr>
<td>Size of glass slide: 22 mm×22 mm×0.15 mm</td>
<td>Contact force ≤ weight of stamp</td>
</tr>
<tr>
<td>Device footprint &lt; 30 cm×30 cm</td>
<td>Speed of contact &lt; 1 mm/s</td>
</tr>
<tr>
<td>Stamp capacity &gt; 1</td>
<td>Vertical travel: 5-15 mm</td>
</tr>
</tbody>
</table>

**SELF-ALIGNING IMPRINTING AND SCALABILITY**

**Self-aligning imprinting scheme**

DCI yield is low due to breakage of the gold coated DNA nanowires during manual imprinting. Breakage occurs due to (i) large in-plane stamp motions and (ii) high contact forces. Thus, yield can be improved by controlling the in-plane motions and the contact forces as the stamp is brought in contact with the glass surface. However, simultaneous control of these parameters is currently not possible via other established imprinting processes. In our self-aligning technique, we allow the stamp’s own weight to align itself parallel to the glass slide. The stamp is not rigidly attached to the tray/stage; instead, it sits on top of a slot in the tray as shown in Fig. 2. As the stage holding the glass slide is actuated up, the stamp makes contact with the glass surface, tilts and partially loses contact with the tray. Friction at the stamp-glass interface ensures that the stamp does not slide on the glass surface. On further actuation of the glass slide, the entire stamp loses contact with the tray and it sits completely on the glass surface, thereby ensuring a conformal contact. This scheme ensures that (i) in-plane motions are minimal during imprinting and (ii) contact forces don’t exceed the stamp weight.

**Sources of misalignments**

The self-aligning scheme enables scalable imprinting via (i) parallelization and (ii) reduced complexity of the motion stage. Parallelization is feasible via this scheme as several stamps can be simultaneously aligned by supporting them on a common tray. Complexity of the motion stage is substantially reduced as a simplified single degree-of-freedom linear motion stage may be used for actuation. Also, feedback position control of the motion stage is not essential anymore; instead position control may be implemented simply by an on-off switch that indicates the end of alignment. This is because post-alignment the stamp is supported entirely by the glass slide. Thus, contact forces are insensitive to the position of the glass slide after alignment is achieved.
shown in Fig. 3, prior to imprinting, the glass slide and the stamp may not be parallel to each other due to the following angular misalignments: (i) parallelism error between the stamp and slide trays, (ii) misalignment between the stamp surface and the platform, and (iii) misalignment between the glass slide and the platform. In addition, during motion of the platform, parallelism between the platforms may change due to the parasitic motions of the linear stage.

Later we measure and characterize these misalignments for our scalability of the device to the various angular misalignments. Thus, scalability of the device to tolerate these misalignments reduces, i.e., conformal contact may not be achieved over all the stamps. These three conditions constrain the feasible range of motion during imprinting. Scalability may be obtained by linking the gap between the trays to the angular misalignments and enforcing these constraints.

The effect of all three misalignments can be combined by considering the worst case scenario, i.e., the orientation in which all the misalignments add up to reduce scalability. Angular misalignment between the stamp tray and slide tray is denoted by $\theta_i$ and the misalignments between stamps/glass slides and their respective trays are denoted as $\theta_s$ and $\theta_g$. Also, the stamp has a length of $l_s$, a thickness of $t_s$ and a thickness variation of $\delta_s$. Similarly, the glass slide has a length of $l_g$, a thickness of $t_g$ and a thickness variation of $\delta_g$. If $h_o$ is the shortest distance between the trays in the open position, then the gap $g_i$ between the lower surface of the stamp and the top surface of the glass slide is given by:

$$g_i = h_o - \left( t_g + l_g \theta_g - l_s \theta_s \right) + (t_s + \delta_s) + (t_g + \delta_g)$$

Enforcing the constraint that this gap is at least above the threshold value of $g_{\min}$ gives:

$$h_o \geq g_{\min} + \left( t_g + l_g \theta_g - l_s \theta_s \right) + (t_s + \delta_s) + (t_g + \delta_g)$$

If $p_s$ is the pitch of the glass slide arrangement and $N$ is the number of stamps, then the gap between the trays in the closed position $h_c$ is given by:

$$h_c = (t_s - \delta_s) + (t_g - \delta_g) - (N - 1)p_s + l_s \theta_i$$

Enforcing the constraint that this gap is at least above the threshold value of $h_{\min}$ gives:

$$N \leq 1 + \frac{(t_s - \delta_s) + (t_g - \delta_g) - (h_{\min} + l_s \theta_i)}{p_s \theta_i}$$

Also, the condition that the glass slides do not hit the stamp tray gives:

$$\theta_s + \theta_g \leq \frac{h_{\min} - (t_s + \delta_s)}{l_s}$$

Thus, scalability of the device is given by Eqs. 2, 4, and 5 and the range of motion of the stage for a complete imprinting cycle is given by:

Scalability model

We define scalability of the device as the maximum number of stamps ($N$) that can be simultaneously aligned in the presence of angular misalignments. Alternatively, scalability may also be represented as the maximum misalignment that can be tolerated for a given number of stamps. The stage has two operational states: open and closed. In the open state, the stamp and slide trays are loaded onto the platforms and are separated from each other. In this state, the gap between the trays should be such that none of the stamps make contact with the glass slides and there is sufficient gap to perform loading and/or unloading of the trays without contact. In the closed state, the tray that holds the glass slides is actuated up so that all the glass slides make contact with the corresponding stamps above them. During this state, the gap between the trays should be sufficiently high to allow access for the fluid dispensing needle into the gap between the trays. Also, none of the glass slides should hit the tray that holds the stamps. These three conditions constrain the feasible range of motion during imprinting.

Fig. 3: Trays with angular misalignments. (a) In open state and (b) in closed state.

The tray misalignment is primarily a function of the quality of the kinematic coupling and the alignment of the platforms, while the other two misalignments are determined by the quality of the fixtures holding the stamps and slides in their respective trays. In addition, the quality of machining affects all three of these misalignments, as the repeatability and precision of the machine or fabrication method introduce errors and misalignments between parts of the system. As the size of the trays is increased, the ability of the device to tolerate these misalignments reduces, i.e., conformal contact may not be achieved over all the stamps. Thus, scalability of the device reduces with an increase in misalignment. Herein, we relate the scalability of the device to the various angular misalignments. Later we measure and characterize these misalignments for our stage and evaluate the scalability of the fabricated device.
\[ Z_n = h_n - h_{\text{min}} \]  

(6)

**DESIGN OF THE AUTOMATED STAGE**

We have designed a scalable stage that can simultaneously handle three stamps and is capable of further scale-up. A model and picture of the stage is shown in Fig. 4. The stage consists of a C-type frame with a movable platform that is actuated via a stepper motor. Stamps are loaded into a tray that is mounted on a fixed platform via kinematic couplings. Similarly, glass slides are loaded into a tray that is mounted onto the movable platform via kinematic couplings. This allows one to rapidly attach and detach the trays from the stage and also makes it possible to handle fragile stamps during loading/unloading. For example, the entire stamp holder tray can be inserted into the gold evaporator, taken out and then attached to the imprinting stage without any need to individually handle the stamps. Scaling-up the system would involve using a larger stamp holder and is limited only by the size of the UV source used for curing and the size of the gold evaporator. For alignment and imprinting, the lower slide tray is driven up toward the stamp tray, and the stamps are brought into contact with the slides. A contact switch stops the tray motion at the desired height. A UV light source underneath the slide trays provides the energy to photo-cure the monomer solution that is dispensed at the stamp/glass interface. Upon photo-curing, the platforms are separated and the stamps and glass slides are unloaded.

During operation of the device, only one of the platforms is actuated while the other one is held fixed to the stationary side-bracket. It is possible to reconfigure the device to so that either the top or the bottom platform is actuated. This reconfiguration is achieved by engaging the lead screw to the corresponding platform via a flexible split nut. Both the top and bottom platforms feature pockets for the split nut, allowing the lead screw to drive either the top or the bottom stage. To reduce stiction during actuation, the split nut was fabricated from Teflon. Herein, we run the device with the top platform held fixed to the support structure.

**Motor Control**

A Vexta PK243-01AA stepper motor was used in this device that has a basic step angle of 1.8° and holds a torque of 0.2 N-m [8]. The stepper motor is driven in open loop so that the position and speed of the moving platform is controlled via inputs to the stepper motor. A mechanical limit switch is used to determine the stop position of the platform. The motor responds to a square wave input, making 1 step for each rising edge. Each step consists of a rotation of a fixed step angle (\( \theta \)), which depends on the configuration of the motor controller and the step angle of the motor. The stepper motor is powered by the Interinar BSD-013G-8 motor controller [9] and an external signal generator is used to provide the step signal. The linear actuation speed of the platform is adjusted by changing the frequency of the step signal (\( f \)). The linear speed of the platform (\( V \)) is given in terms of the pitch of the lead screw (\( p \)) by:

\[ V = p f \frac{\theta}{360^\circ} \]  

(7)

Herein, we have (i) used an eighth-step motor controller that gives \( \theta = 0.225^\circ \), (ii) used a 1/4 -20 inch lead screw that gives \( p = 1.27 \) mm/rotation, and (iii) run the motor at 200-400 Hz. Correspondingly, the linear speed of the platform is about 160-320 \( \mu \)m/s. With an imprinting stroke length of 10 mm, this corresponds to a cycle time of ~0.5-1 min for the stamp/glass self-alignment operation.

**Position sensing**

Position sensing is required to ensure that there is sufficient actuation of the platform to allow for the stamps to align with the glass slides. Position sensing is achieved via an on/off limit switch that turns the motor off as soon as the gap between the platforms reaches a pre-determined threshold. This threshold...
gap between the top and bottom platforms is set by a mechanical/electrical limit switch. The switch consists of a dowel pin mounted on the lower platform and an adjustable ball-tipped screw mounted on the top platform. The ball-tipped screw may be used to adjust the gap between the two platforms. To perform alignment, the top/bottom platform is actuated until the dowel pin and the screw make contact. As the dowel pin is electrically insulated from the rest of the device, signal from this mechanical contact is used to switch off the motor.

**Material Handling**

In order to reduce the defects due to material handling, individual stamps are not handled during the gold evaporation or imprinting steps; instead, individual stamps are loaded onto a common tray. This tray is used for (i) holding the stamps during evaporation and imprinting and (ii) for transferring the stamps from the evaporation chamber to the imprinting stage. Glass slides are also loaded on a common tray that is mounted onto the bottom platform of the motion stage. The trays are mounted onto the platforms via 3 ball and V-groove kinematic couplings. Both the top and bottom platforms feature either precision balls or grooves for the kinematic couplings. This interface enables rapid reconfiguration of the system to utilize different arrangements of stamps/slides by simply replacing the trays that hold the stamps/slides. Magnetic preload was added via permanent magnets attached to the center of each coupling. This ensures a firm seating of the kinematic couplings and prevents tipping of the trays. Magnetic preload was chosen over mechanical fasteners for its ease of engagement, as it allows the couplings to be readily engaged or disengaged during operation.

![Tray for stamps](Image)

To demonstrate parallel self-alignment we have designed and fabricated a stamp tray that simultaneously holds three stamps. As the tray is designed to hold the stamp both during evaporation and imprinting, the tray size is limited by the size of the evaporator chamber to about 14.5 cm. To load the stamps onto the tray, each stamp is first rigidly attached to a holder plate via adhesive tape. The holder is fabricated from a thin sheet of aluminum and supports the stamp on the tray. The stamps are loaded into the cavities on the tray as shown in Fig 5. A cover plate is then fastened on top of these cavities. The stamp holder plate sits on top of this cover plate when the tray is inverted for the imprinting process. The stamps are constrained in-plane by the cavity side-walls. To enable self-alignment of the stamps, it is necessary for the stamp holder cavities to be relatively deep. However, if the stamps sit on the bottom of the cavity when the stamp tray is upright, it is possible that the stamp surfaces would rub against the edges of the cover plate upon tray inversion. This could damage the stamps and reduce the yield of the process. To minimize these defects, we have designed a gravity-driven pin system to support the stamps when the tray is upright. This mechanism uses a lever to provide an upward force on the stamps. When the tray is inverted, the force is removed, and the stamps are free to self-align as designed. In order to provide a stable platform when loading and unloading stamps from the tray, a set of 3 pins was added to the back of the tray. These pins allow the stamp holder to be placed on a flat surface for loading without wobbling, and protect the gravity-driven pin mechanism.

![Tray for glass slides](Image)

The tray for holding the glass slides, shown in Fig. 6, has fewer features than the stamp tray. Like the stamp tray, it features a removable lid to restrain the glass slides from being pulled away from the tray when the platforms are separated after UV curing. To allow for transmission of UV light from beneath the tray, the slide tray was designed with large holes. The glass slides sit on top of these holes and are constrained in-plane via alignment edges. These edges are formed from the shallow pockets that are machined on the top surface of the tray.
Performance evaluation of the stage

Characterization of the motion stage

The motion of the imprinting stage was analyzed in terms of (i) initial parallelism, (ii) repeatability over multiple cycles, and (iii) parasitic motions within each cycle. One cycle is defined as the movement from an open state, to closed, and then back to open again. The parallelism measurements were performed using digital calipers to measure the tip and tilt of the stages relative to each other. The repeatability analysis, shown in Table 3, was performed using dial gages to measure the in-plane displacements of the moving platform during motion and represents variations in the platform position from cycle to cycle. However, because the stage was measured during motion, it was not possible to measure the tip and tilt variations and these variations are unknown. The parasitic motion analysis, shown in Table 4, represents variation in the tray’s translation and rotation when traveling from the open position to the closed position.

Table 3: Repeatability of linear motion stage

<table>
<thead>
<tr>
<th>Direction</th>
<th>Open</th>
<th>Closed</th>
</tr>
</thead>
<tbody>
<tr>
<td>x translation</td>
<td>0.60±12.7 μm</td>
<td>0.55±12.7 μm</td>
</tr>
<tr>
<td>y translation</td>
<td>-0.07±12.7 μm</td>
<td>-0.06±12.7 μm</td>
</tr>
<tr>
<td>In-plane rotation</td>
<td>11.2±70.9 μrad</td>
<td>10.1±32.5 μrad</td>
</tr>
</tbody>
</table>

Table 4: Parasitic motion of the linear stage

<table>
<thead>
<tr>
<th>Direction</th>
<th>Parasitic motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>x translation</td>
<td>0.06±12.7 μm</td>
</tr>
<tr>
<td>y translation</td>
<td>-0.006±12.7 μm</td>
</tr>
<tr>
<td>In-plane rotation</td>
<td>-1.02±70.9 μrad</td>
</tr>
</tbody>
</table>

The platforms were shimmed after an initial parallelism measurement and the values shown here are those measured after shimming. The final parallelism of the platforms was found to be within 0.65 ± 0.39 mrad along the common central axis of the stamps and 2.46 ± 0.47 mrad along the axis perpendicular to the common center. The repeatability of stage motion was found to be better than the resolution of the dial gages (12.7 μm). From cycle to cycle, the lower stage holding the slide tray experiences small in-plane rotations. Similarly, the variations in x and y positions, measured as translations, were also very low for the linear stage. While the resolution of our data is limited, this still allows us to quantify that the repeatability of the stage’s position from cycle to cycle is very high, and should have little effect on the scalability of the device. During parasitic motion analysis, it was found that the in-plane x and y translations during the transition from open to closed were very low and outside the resolution of the dial gages. Similarly, it was found that on average, the in-plane parasitic rotation is smaller than the measurement resolution, and has a negligible effect on the scalability of the device.

Performance of fixtures

Examination of the kinematic couplings used in the platform-tray interface found that the kinematic couplings were repeatable to within tens of micrometers and tens of micro-radians, or less. The repeatability of all three translational degrees of freedom of the kinematic couplings exceeded the resolution of the dial gages used in measurement (12.7 μm). This corresponds to a tip/tilt misalignment of 0.35 mrad. As discussed later, the tolerable tray misalignment is much higher than this and is ~ 40 mrad. Thus, repeatability of the kinematic couplings is not a major factor contributing to angular misalignments.

Precision of the fixtures that hold the stamps and slides onto the trays determine the angular misalignments $\theta_s$ and $\theta_g$ that in turn affect the scalability of the device. Fixtures were fabricated on an Intellitek Benchman MX vertical mill, that has a machining accuracy of $\delta_m=5 \mu$m.[10] Angular misalignments between the stamp/slide and the trays would arise due to variations in height of the fixture across the width of the stamp/slide. On considering a maximum fabrication error in fixture height of $4\delta_m$ over the width of the stamp holder and $2\delta_m$ over the width of the glass slide, we estimate $\theta_s=1.14$ mrad and $\theta_g=0.45$ mrad. These misalignments are much less than the tolerable angular misalignments for the stamp and the glass slide.

Summary of stage performance

Performance of the imprinting stage is summarized in Table 5.

Table 5: Performance of the imprinting stage

<table>
<thead>
<tr>
<th>Metric</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerable angular misalignment</td>
<td>&lt; 2.3°</td>
</tr>
<tr>
<td>Stamp capacity</td>
<td>3</td>
</tr>
<tr>
<td>Speed of contact</td>
<td>160 – 320 μm/s</td>
</tr>
<tr>
<td>Vertical travel</td>
<td>15 mm</td>
</tr>
<tr>
<td>Displacement resolution</td>
<td>0.8 μm</td>
</tr>
<tr>
<td>Footprint</td>
<td>10 cm × 10 cm × 20 cm (height)</td>
</tr>
</tbody>
</table>
SCALABILITY ANALYSIS AND IMPRINTING RESULTS

Scalability analysis

We can evaluate the scalability of our device using the scalability model that was developed earlier. To quantify scalability, we determine the maximum tolerable misalignment angles ($\theta_s$, $\theta_g$, and $\theta_t$) for a fixed number of stamps. This device was designed to handle $N=3$ stamps at a pitch $p_g=26$ mm. The minimum gap for allowing access for the monomer dispensing nozzle is $h_{min}=4.5$ mm. Also, the stamp has a length of $l_s=10$ mm, a thickness of $t_s=8$ mm and a thickness variation of $\delta_s=0.7$ mm. Similarly, the glass slide has a length of $l_g=22$ mm, a thickness of $t_g=0.15$ mm and a thickness variation of $\delta_g=0.02$ mm. The shortest distance in the open position $h_o$ is arbitrarily chosen to be 12.5 mm such that it satisfies the constraint given by Eq. 2. These parameters were used with Eqs. 2, 4 and 5 to solve for the maximum possible misalignment for each of the three misalignment angles shown in Fig. 3. Each maximum misalignment was found by setting the other two misalignment angles to 0. The tolerable angular misalignments are $\theta_s=20.8^o$, $\theta_g=11.4^o$ and $\theta_t=2.3^o$.

Imprinting results

Feasibility of self-aligning imprinting

Experiments have been performed with micro-ridge patterned stamps both with and without DNA nanowires. Arrays of nano-channels fabricated with this stamp pattern are useful for nano-electroporation studies [5]. The experiments were performed on a manually actuated motion stage so as to provide a preliminary feasibility assessment of the self-aligning technique. The results are shown in Fig. 7. Imprinting without DNA nanowires demonstrates conformal contact (Fig. 7(a)) over a large area. For the experiments with DNA nanowires, individual nano-channels were identified across the micro reservoirs (Fig. 7(b)). We are currently developing a rapid imaging technique to quantify the imprinting yield by identifying and counting the nano-channels over a large area of the chip.

Multi-stamp self-alignment

While the model has shown the device to be scalable, we simulated an imprinting cycle on the device to verify its self-aligning capability. Using uncoated stamps and glass slides, we loaded the sample trays just as we would for a full imprinting cycle, and ran the device. Qualitatively, the device performed as expected, i.e., all three stamps made conformal contact with their respective slides. At the closed position, the gap between the sample trays is approximately $6$ mm $> h_{min}$, this gap is sufficiently large to allow access for a dispensing nozzle. The closed position of the stage is shown in Fig. 8.

Next, we introduced an intentional misalignment between one of the glass slides and the tray and repeated the alignment procedure. As shown in Fig. 8(b), one side of a slide was propped up, causing an angular misalignment between the glass slide and the slide tray ($\theta_g$) of approximately $5^o$. The imprinting cycle was run again, and in the closed position, it was observed that all three stamps are aligned with the glass slides, thereby demonstrating simultaneous self-alignment. The distance between the stamp and slide trays was measured to be 4.8 mm, which is still higher than the minimum gap ($h_{min}$) of 4.5 mm. In future, the performance of the stage will be further verified by performing imprinting and pattern transfer with stamps that have DNA nanowires on them.

CONCLUSIONS

Herein, we have developed a self-aligning technique that enables scalable automation of imprinting. Imprinting with a manual stage has demonstrated the feasibility of this alignment scheme. The self-alignment scheme was implemented on an
automated motion stage that can align three stamps at a time. The motion stage was found to have in-plane parasitic motions that are lower than the measurement resolution of the dial gage (12.7 μm). We also developed a model to link the scalability of the stage to the angular misalignments between the stamp and the glass slide. This model was used to predict the tolerable angular misalignments for simultaneous imprinting of three stamps. The tolerable misalignments were found to be $\theta_s=20.8^\circ$ between the stamp and its tray, $\theta_g=11.4^\circ$ between the glass slide and its tray and $\theta_t=2.3^\circ$ between the two trays. Experiments that were performed to test the alignment capability of the stage verify that conformal stamp contact can be achieved across all three stamps even in the presence of a misalignment of 5° between the glass slide and its tray. This ability to simultaneously align multiple stamps is a critical step in being able to scale-up and fully automate the DCI process.

Although the imprinting stage enables simultaneous alignment of several stamps, the yield of the stage is currently unknown. For this stage to be an effective replacement for the manual process, it is important that the yield on this stage is higher than the manual process. In future, we will quantify the imprinting yield on this stage and compare it to the manual process. Yield on this stage may be improved by incorporating a force control mechanism into the self-alignment scheme; for example, by applying an external force opposite to the weight of the stamp. Also, appropriate fixtures for holding the stamps/slides onto the trays may need to be implemented in the future to perform in-plane alignments in addition to the existing capability to perform out-of-plane alignment. Although in-plane alignment is not essential for improving the imprinting yield, such alignments may be necessary for applications that require multi-step alignment or alignment to pre-existing features on the substrate.

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REFERENCES


