DESIGN OF A PRECISION TRANSFER LINE FOR DIP-PEN NANOLITHOGRAPHY

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SYNOPSIS

In this paper we describe a precision indexing system that was designed as a scalable, probe-based fabrication system for high-rate, mass nanomanufacturing. This system is roughly the size of a "bread box", and contains a precision belt-drive that has been designed to enable continuous processing of substrates as dies or continuous ribbons/webbs. This approach enables nanofabrication over a large area without the need for large, expensive, high-speed precision motion stages. Here we bring the substrate to/from the processing area via 'web transport.' We envision this technology will (a) provide a means to transform probe-based nanofabrication processes into practical high-volume nano-manufacturing processes and (b) enable parallel probe-based processing of biological specimens (e.g. stem cells) during factorial experiments.

INTRODUCTION

In probe-based nanomanufacturing (PBN) micro-scale probe tips are used to make, manipulate, or measure nm-scale features on a substrate. Two important issues for PBN are cost appropriate equipment that can (i) deliver the desired rate and (ii) process large (1000s cm$^2$ or more) substrate surface areas. The rate issue is being addressed by the use of 2D probe arrays that consist of up to 55,000 tips [1]. This leads to the need for 6 axis positioning equipment that can position the probes and level the array with respect to the substrate surface. The 'processed area' issue has yet to be resolved due mainly to the perception that the solution is in old paradigms, e.g. equipment that travel over large surfaces with nm-level resolution. In this approach, achieving suitable cost with six-axis nanopositioning is difficult.

In this paper we describe the design and early experimental characterization of a prototype precision indexing system that combines a six-axis flexure system, an array of probe tips and precision belt-drive. The system is shown in Fig. 1 and its main components are shown in Fig. 2. This combination enables (i) continuous fabrication – moving long webs/ribbons of a substrate material within a nanofabrication processing center, or (ii) semi-continuous fabrication – moving arrays of dies/chips atop a belt “transfer line” that moves dies/chips within a nanofabrication processing center. The system is designed to meet the needs of general PBN processes that require high rate and large area processing. The utility of the system is best described in the context of a specific process, therefore we will use dip pen nanolithography (DPN) as the example.

FIGURE 1: Prototype DPN transfer line and HexFlex-based processing center.
Overview of DPN processing

DPN is a PBM process wherein a material, e.g. ink, is deposited onto substrates with feature sizes down to 15nm [2]. The “ink” is written upon a substrate via an AFM-like tip. Figure 3 shows how this process happens [3]. As the tip is dragged across a substrate, ink diffuses from the tip to the substrate via a nano-scale water meniscus. The meniscus forms spontaneously via capillary condensation [4].

Case study

DPN, and most other PBN processes, are viable fabrication processes, but a means to process many dies and/or large area substrates is needed for industry application. Our case study is based upon a need expressed by the Ohio State’s Center for Affordable Nanoengineering of Polymer Biomedical Devices. They create arrays of DNA bundles for subsequent processing by writing of chemical agents upon the bundles. Each bundle of DNA contains approximately ten strands, and each strand of weighs approximately $5.23 \times 10^{-20}$ kg. At best, meaning if processing yield is 100%, each time a 50,000 probe tip array writes upon a DNA array it is processing approximately 29 pg of DNA. If processing of arrays occurs at 0.1 Hz, then a single array has a 2.9 pg/sec processing rate. This logic is carried out to provide estimates for production rate in Table 1.

### TABLE 1. DNA production rate

<table>
<thead>
<tr>
<th>Required DNA</th>
<th>100</th>
<th>μg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tips/array</td>
<td>55000</td>
<td>Tips</td>
</tr>
<tr>
<td>Number of arrays</td>
<td>1</td>
<td>Trays</td>
</tr>
<tr>
<td>Number of arrays</td>
<td>1</td>
<td>Samples</td>
</tr>
<tr>
<td>Cycling frequency</td>
<td>0.1</td>
<td>Hz</td>
</tr>
<tr>
<td>Best case yield</td>
<td>100</td>
<td>%</td>
</tr>
<tr>
<td>Processing time</td>
<td>402.4</td>
<td>Days</td>
</tr>
<tr>
<td>Production rate</td>
<td>0.25</td>
<td>μg/day</td>
</tr>
</tbody>
</table>

The purpose of processing the DNA is personal drug development, e.g. custom drugs for genetic diseases, 402 days is clearly too long. The processing center has been designed for high throughput and reduced processing time.

EQUIPMENT FUNCTIONS AND PROCESSING

The transfer line provides long-range indexing of substrate material into, and out of, the system. Material flow and processing steps are best understood via Fig. 4. The substrates are indexed beneath a 1cm$^2$ array of probe tips that are attached to a meso-scale HexFlex [5]. A flexible linear scale is affixed to the edge of the belt and follows the belt through the system. A read head records the motion of the belt, thereby providing the means for fine resolution position control of belt/web indexing.

An air piston, positioned below HexFlex station, presses the belt and substrate up to the HexFlex. The substrate material (die or web) contains kinematic alignment features (grooves)
that engage with mating features (balls) which are attached to the HexFlex mount. The kinematic features align the substrate to the HexFlex within +/- 300 nm (0.3µm). The HexFlex is a six-axis flexure that performs fine alignment (nm-level position and µradian parallelism beyond the KC’s performance) between the probe tip array and substrate. The HexFlex has a range of motion of 50µm x 50µm x 50µm. It then puts the array in contact with the substrate and moves the probe tips across the substrate’s surface during processing. When processing of the local area is complete, the transport system indexes a new substrate below the HexFlex, the position/orientation of the new substrate is registered, and the cycle repeats.

DESIGN

The housing and structure of the prototype was constructed through the use of a square aluminum extrusion. This design is used to reduce complexity/part count, and isolate the processing zone from the environment. A large hole in the top of the tube receives and houses the HexFlex nanopositioner sub-system. The two holes in the side receive inserts that contain the rollers’ alignment flexures.

Quasi-kinematic couplings [6, 7] are used to ensure precision alignment (e.g. during tool changes or maintenance) and provide sealing contact between the inserts and the tube. The rollers, which support and drive the web/belt, are assembled between the side inserts. Sets of kinematic couplings are used to align the substrate to the HexFlex, the HexFlex to its insert, and this insert to the structural tube. The HexFlex-substrate KC has a capture distance of ~250 microns. Technically, the indexing system need only position the substrate to within this distance to permit engagement of the coupling, but coupling repeatability improves when the balls-grooves are better aligned prior to mating.

This tubular architecture was selected as this design may be scaled to include other parts of a nanomanufacturing system. We envision that several segments of tubes (the prototype segment is approximately 30 cm long) may be coupled together by kinematic couplings. Each segment would be specifically designed for a different fabrication process. The connected segments would form a low-cost, modular, flexible ‘manufacturing line’, wherein the environment in each segment may be controlled.

COUPLING PERFORMANCE

We have already demonstrated processing capability with the HexFlex sub-system [5]; therefore we focus here on the performance of the new elements: the indexing system and substrate-HexFlex kinematic mounting system. For a typical probe-based manufacturing system, the plane of probes and substrate plane must be aligned within a few µrads to set the spacing of the substrate and probes to avoid crashing or too large a gap between probe and substrate. In DPN, the probe tips rest on compliant cantilevers and the process is meant to be conducted with tips in contact. The leveling constraints here, 800 µrad, are less stringent.

Three capacitance probes were used to measure the leveling repeatability of the substrate-HexFlex coupling. Figure 5 shows the probes within the device and Fig. 6 shows the positions of the probes relative to the substrate-HexFlex kinematic coupling.

![FIGURE 5: Measurement setup](image)

![FIGURE 6: Capacitance probes position relative to kinematic coupling grooves](image)
direction). The substrate was then preloaded onto its kinematic mounts via the air piston, and then the system was allowed to settle.

The repeatability data are plotted in Figures 7 and 8. The repeatability in z was +/- 300 nm. This is within the HexFlex’s vertical range of motion (12 µm) and better than the z alignment of 6 µm required for the probe tips. The initial transient position in Fig. 7 is indicative of a coupling wear-in period and was expected. The repeatability was therefore calculated using the stabilized readings, i.e. cycles 11–40.

![Substrate Kinematic Coupling Repeatability](image1)

**FIGURE 7. Z axis repeatability**

The repeatability in tip-tilt, shown in Fig. 7, was +/- 20 µrads. This is 40 times better than the requirements of DPN but on the order of performance that most probe-based processes will require. The contrast between required and achieved performance is listed in Table 2.

![Substrate Kinematic Coupling Angular Error](image2)

**FIGURE 8. Tip and tilt repeatability (error bars are smaller than data points)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Required</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical offset (z)</td>
<td>+/- 6 um</td>
<td>+/- 300 nm</td>
</tr>
<tr>
<td>Angular error (θₓ, θᵧ)</td>
<td>+/- 800 µrad</td>
<td>+/- 20 µrad</td>
</tr>
</tbody>
</table>

**TABLE 2. Required/measured performance**

**CONCLUSION**

These experiments are the first conducted on the prototype. We envision further optimization of the system (e.g. improved friction management via flexures [8, 9]) will improve repeatability by a factor of two or more. Our next steps encompass the integration of many 55,000 tip arrays to increase throughput.

**REFERENCES**


