Design and Manufacturing of High Precision Roll-to-Roll Multilayer Printing Machine – Machine Upgrade

by

Yufei Zhu

B.S., Measurement, Control Technology and Instruments (2008)

Tsinghua University

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Master of Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

August 2009

Signature of Author: ....
Department of Mechanical Engineering
August 18, 2009

Certified by: ....
David E. Hardt
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by: ....
David E. Hardt
Chairman, Departmental Committee on Graduate Studies
Department of Mechanical Engineering

Design and Manufacturing of High Precision Roll-to-Roll Multilayer Printing Machine – Machine Upgrade

by

Yufei Zhu

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of
Master of Engineering

Abstract

In 2008, a group of MIT Master of Engineering students built a roll to roll machine for printing thiol onto a flexible gold substrate by self-assembly. The machine demonstrated good performance in high speed printing (400 ft/min). Since single layer printing is limited in industrial application, we reconfigured this machine for multi-layer printing . Our project includes developing a device that can fabricate high quality stamps, which is vital in print quality; increasing the roll to roll machine accuracy in critical components, which helps increases the machine's repeatability. In addition, we have designed a multilayer printing system using the same technology and demonstrated it with the upgraded machine. The flat stamp cast by the new machine can achieve the flatness of ±16μm with thickness of 1194μm, compared to ±32μm of stamp made with other machine. An initial experiment with multi-layer printing using the upgraded machine has shown that better control of the roll drive system and better registration measurement will be required to meet the necessary specification. However, the first experiment did can achieve alignment errors of 1017μm along the printing direction and 113μm across the printing direction

Thesis Supervisor: Dr. David E. Hardt
Title: Professor of Mechanical Engineering

Acknowledgement

It's an unforgettable experience to work with my great teammates: Wenzhuo Yang, Paolo Baldesi and Charu Datar. From exchanging ideas at the beginning to the final experiments on the devices we designed together, pleasure and excitement was filled all over the project as we work together.

I'm deeply appreciated for the insight suggestions and guidance from Professor David E. Hardt. He always inspires us in the project, and all we learned from Prof. Hardt is a life-long treasury.

Many thanks to Nano-Terra Inc. for providing us the opportunity to work on this project. The unlimited resource and suggestions coming from the company lead us to finish our machines. Dr. Igor Sokolik and Dr. Brian Mayers have acquainted us with the process, and Dr. Shih-Chi Chen as well as Werner Menzi instructed us in our mechanical design. Their effort enables us to successfully finish the project.

TABLE OF CONTENT

List of Figures

List of Tables

1. Introduction

1.1 Motivation

Currently, nanostructures are commonly fabricated using techniques such as photolithography, electron-beam writing and X-ray lithography. Although these methods are proven technologies that provide high-quality outputs, there are inherent problems. These techniques are generally expensive, slow, and the production of large patterns is difficult. Micro-contact printing (μCP) is a promising technology in which a patterned elastomeric stamp is used to transfer patterns of self-assembled monolayer (SAMs) onto a substrate by conformal contact printing. In 2008, a group of MIT students developed a high throughput, low cost roll-to-roll (R2R) printing technique into micro-contact printing, achieving good results. They also built a prototype machine to realize the whole process in the speed of 400 feet per minute while maintaining good quality outputs.

However, the last year's machine is only limited to printing octadecanethiols, an organic ink, on gold substrates where the self-assembly characteristics (see section 2.1) of these media could tolerate big range of pressure variance applied on the substrate. Therefore, if the micro-contact printing is applied into some other media where self-assembly characteristics do not exist, a highly uniform pressure along the substrate will be critical to the quality of outputs. The pressure of previous prototype machine is provided by the contact of the print roller and the impression roller. The uniform roundness and straightness of the rollers is key to the uniform pressure along the contact area. Meanwhile the parallel contact between the impression roller and the printer roller is also very important. Therefore, if we can fabricate the print roller with the variance less than a few microns and the contact between the impression roller and the printer roller has good parallelism with high repeatability, then the roll-to-roll micro-contact printing technology could be easily applied to various printing media.

The printer roller consists of central shaft, sleeve, the backing plate and the stamp (see section 2.2). The uniform thickness of the stamp is the most critical component of the uniform roundness of the print roller. Currently, there is no standard process to fabricate the stamp with the thickness variance of a few microns, therefore, the repeatable, reliable and manufacturable stamp fabrication process is also highly desired.

Another limitation of last year's project is that the registration of multiple layers on a flying substrate was not considered; only monolayer could be printed using the prototype machine. However, in the industry, multi-layer printing is required, which means to print another layer on the substrate with patterns. At present, the commercial printing industry, where multi-layer printing is very common and popular, can only achieve a resolution of 40 microns. Thus, such technology can hardly be applied to multi-layer printing where the pixel size is less than 40 microns. If multi-layer printing with the resolution of 1 micron could be demonstrated by upgrading the previous prototype machine, there will be a significant impact in the printing industry.

Research was funded by and in cooperation with Nano-Terra Inc, a Cambridge, Massachusetts company that specializes in Soft Lithography.

1.2 Problem Statement

The primary objective of this project is to address the limitations of the previous prototype machine in related to the potential manufacturing of printed electronics using micro-contact printing technique within the soft lithography (SL) field.

At first glance, the main goals of this project can be split in two major areas:

1. Improve the printing quality, upgrading the R2R system built by the MIT students in 2008; in particular this goal will be achieved by designing and fabricating an interchangeable stamp on the roller that allows a quick replacement of the stamp once it is used up, without losing of alignment. This goal is achieved by performing three key steps:
    - Design of an interchangeable stamp.
    - Fabrication and demonstration of interchangeable stamp.
    - Test results providing data on distortion, and alignment.
    - Budget estimate for manufacturing applications.

2. The second main goal of the project is to improve the overall R2R system. This task is achieved by executing the following steps:
    - Redesigning and implementing the impression roller system.
    - Designing process for multi-layer printing
    - Designing a high precision positioning system.
    - Test results providing data on distortion and alignment.
    - Budget estimate for manufacturing applications.

1.3 Primary Analysis

We considered the two major goals of the project, namely, fabricating a very flat stamp and then wrapping it around the print roller, and proving that micro-contact printing can be used for printing multiple layers with alignment.

In order to fulfill these goals, our approach consisted of accomplishing the followings:

1. Flat stamp fabrication. To achieve this, a new method was developed to fabricate the stamp using a molding process, to ensure a flat and defect-free stamp.

2. Wrapping the stamp with backing plate onto the roller with alignment and repeatability. The goals of this process were to wrap the stamp while maintaining alignment, and developing a repeatable process; and to maintain uniform roundness of the stamp after wrapping. To achieve this, after looking at a lot of options, we decided to use a magnetic cylinder, and a pin-slot system to grab the edge of the backing plate. We also considered a fixture system to wrap the stamp with backing plate on the cylinder.

3. Ensuring the roundness of assembled print roller within 4 microns tolerance. With proper wrapping method, minimal and uniform printing pressure could be achieved and hence realized good printing quality.

4. Redesigning the impression roller system to improve its repeatability of parallelism. In this process, we built up error budget model, found out the constraint to the repeatability of the impression roller system and then updated the system.

5. Designing a high precision position system to control the print roller position and orientation. This step was fundamental to improve the quality of single layer printing as well as the multiple layers printing.

6. Printing using the updated machine and comparing results that achieved by last year's group. After we qualified the wrapped stamp and impression roller system, we mounted the new roller onto the current machine, to get a direct comparison of print quality.

7. Printing multiple layers as a proof of concept. This was an independent step, to prove that micro-contact printing can print multiple layers on a single substrate with minimum misalignment.

1.4 Scope

Our project only dealt with micro-contact printing with PDMS as the stamp and 300mm wafer as the master. We focused on printing thiol onto gold-coated substrates. This scope allowed us to decide the dimensions of our design based on available materials. The mature printing mechanism also allowed us to verify our designes without disturbance of different printing conditions.

For multi-layer printing, the initial purpose was to use rigid and transparent material (glass) as the substrate to print two layers using the same stamp to print twice. Later on, the scope switched to using updated R2R machine to print two layers with the same stamp in order to demonstrate what is the best alignment can be achieved using current Roll-to-Roll technology. In order to achieve this target, precise control of the printer roller on its alignment is required and we assumed the motion of the flexible substrate is self-aligned across the printing direction.

1.5 Task Division

This thesis is based on a team project executed as part of the Mechanical Engineering Master of Engineering in Manufacturing Degree Program. The team members were:

Wenzhuo Yang has researched and determined the measurement methods for cylinder roundness, tolerance of stamp fabrication parts as well as the print quality of output features. He designed the measurement structure and analyzed the data obtain from both measurements. In addition, he worked with Yufei Zhu on the upgrade of impression roller system and multi-layer printing process design.

Paolo Baldesi has designed the high precision positioning system to control the position of the print roller. He calibrated the system and determined its performance. In addition, he worked with Charudatta Datar in developing an innovative wrapping process designing a new magnetic print roller. He also researched and designed the mechanism of growing UV-curable material onto cylinder directly.

Charudatta Datar has designed the magnetic roller, and developed the technique to attach and wrap the backing plate and PDMS stamp onto the print roller. He also worked with Paolo Baldesi in designing the high precision positioning system. In addition, he designed other components, compatible the high precision positioning system, to mount the new print roller on the machine built by the MIT '08 team,.

Yufei Zhu designed and constructed the multi-layer printing machine. He also designed the stamp fabrication parts with Mr. Werner Mezi from Nano-terra Inc.

We collectively tested the machine and determined the quality of printing resulted from the machines. Since we were working on a common project, the first three Chapters of our individual theses are common.

2. Literature Review

This section summarizes the existing R2R machine developed in 2008 by Adam Stagnaro, Kanika Khanna, and Xiao Shen [4,20,21], introduced the technologies used in the machine, and described its structure, function, operation steps and the result achieved. Also some pioneering studies of the currently multi-layer printing technology were reviewed to enlighten our prototype design on current R2R machine. Finally, some popular and representative optical metrology systems are studied to search out proper methods for measuring the quality of the machine design and the print output.

2.1 Soft Lithography

Photolithography is a well-established micro-fabrication technology, being widely used to manufacture most integrated circuits. It is, however, limited to a feature size of about 100 nm owing to optical limitations. Technologies such as extreme UV lithography, soft X-ray lithography, electron-beam writing, focused ion beam writing, and proximal-probe lithography[1] are capable of manufacturing smaller features, however, they are limited by high cost and technology development.

Photolithography also has other limitations: it cannot be used on non-planar surfaces; it is incapable of producing three-dimensional structures, and it is not suitable for generating patterns on glass, plastics, ceramics, or carbon [1].

Thus, a family of techniques called as soft lithography, including, microcontact printing, replica molding (REM), microtransfer molding (mTM), micromolding in capillaries (MIMIC), and solvent-assisted micromolding (SAMIM) are emerging as prospective solutions to overcome some of the limitations of photolithography.

They offer a number of basic advantages, such as, little capital investment, and simplicity. Apart from these, soft lithography techniques can produce features smaller than 100 nm, with relatively simple technology, and they are not subject to optical limitations. They also offer flexibility in terms of surface material, and shape, overcoming some of photolithographic limitations.

These techniques are referred to as "soft lithography" because each technique makes use of flexible organic materials as opposed to rigid materials to achieve pattern transfer to the substrate. Basically, these techniques involve the fabrication of an elastomeric stamp (typically made of Polydymethylsiloxane, PDMS), generating a replica of the pattern originally on a Silicon master, and using this stamp to print the pattern on a substrate using self-assembly.

Self-assembly refers to the spontaneous formation of molecules into organized structures by non-covalent forces. The resulting structure is highly uniform, defect-free owing to thermal equilibrium, and in the lowest energy form.

Self-assembled monolayer (SAM) is one such non-biological self-assembly system (see figure 2.1 for its process). SAMs is used in soft lithography to transfer the pattern on the elastomeric stamp, onto the surface of the substrate using minimal contact pressure.

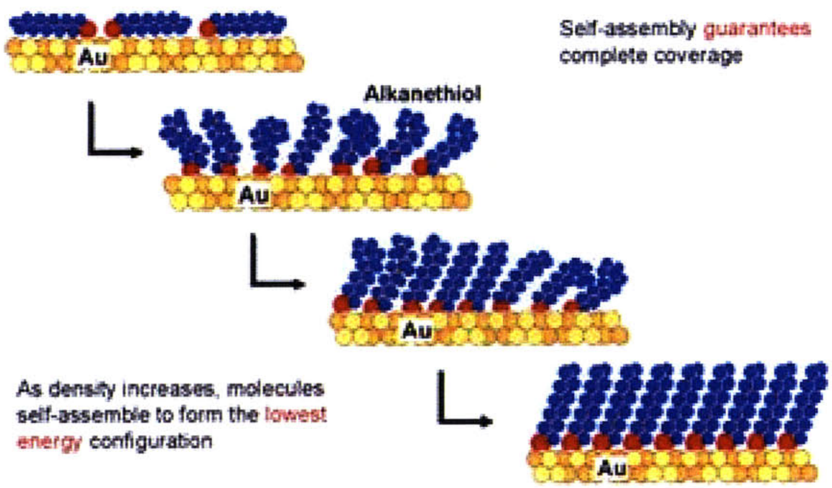


Figure 2.1 Illustration of the self-assembly process [2]

We lay emphasis upon one of soft lithography techniques, micro-contact printing, because we used this method throughout the project. This paper does not describe the other methods.

2.2 Micro-contact Printing

The micro-contact printing process involves transferring a pattern on an elastomeric stamp onto the surface of a substrate by the formation of a monolayer of ink, which can be used as resist in subsequent etching, or other steps. This process relies on SAM, in which it enables transfer of only a monolayer of ink to the substrate. This molecular level contact makes the process independent of excessive ink being trapped between stamp and substrate, allowing significantly smaller sized (~ 50 nm) features to be printed onto the substrate.

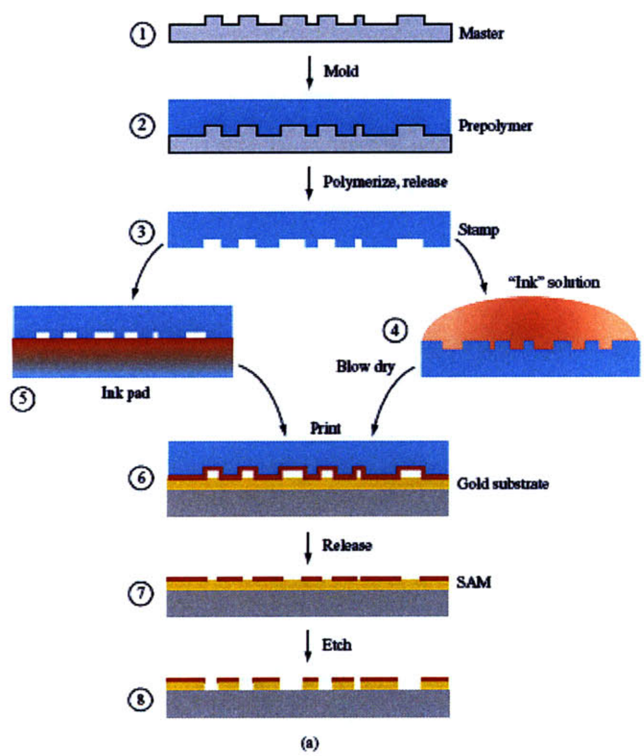


Figure 2.2 Steps Involved in Micro-Contact Printing [3]

The micro-contact printing process, as shown in figure 2.2, involves, like all soft lithography techniques:

1. A master with the original pattern on it. This is typically a patterned Silicon wafer.
2. This pattern is then replicated on a PDMS stamp by casting or molding.
3. This PDMS stamp is then inked, by a couple of methods (using an ink pad, or pouring ink over the stamp).

4. Next, this inked stamp comes into contact with the substrate that is to be printed upon.
5. This contact enables the formation of a SAM of the ink on the surface of the substrate.
6. The stamp is released, and the SAM formed on the substrate is then used in subsequent etching steps to generate the required pattern on the substrate.

2.3 Existing Roll-to-Roll Equipment

The MIT'08 team's (Adam Stagnaro, Kanika Khanna, and Xiao Shen [4,20,21]) task was to take this demonstration to the next level, and prove that the paradigm would be competitive with commercial printing systems in at least one of the parameters - quality, rate, flexibility.

The key goal of this MIT'08 project was to achieve Micro-contact printing at very high speeds (400 ft/min), on 8" wide coated substrate (web).

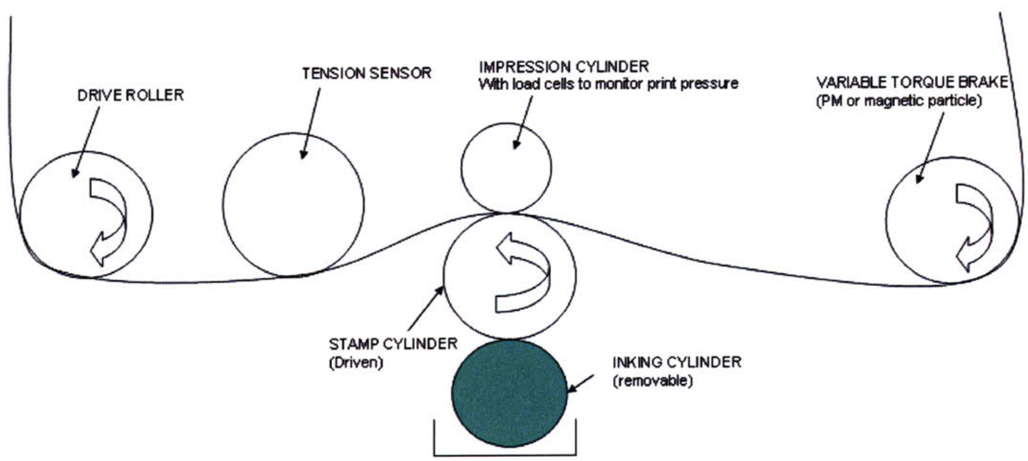


Figure 2.3 Concept of the Machine [4]

The concept of the machine is shown in figure 2.3. The substrate was in the form of a web, driven through a set of rolls. A combination of open and closed loop using motors and clutches was used to achieve tension control.

The equipment can be divided into three modules:

1. Supply Module (to unwind substrate web),
2. Print Module (to ink, print, and apply pressure), and
3. Collect Module (to rewind substrate web) [4]

Figure 2.4 shows the layout of the machine, in terms of these three modules. The entire roller system is cantilevered about a common base plate. And figure 2.5 shows the physical appearance of the R2R machine built by 08' group.

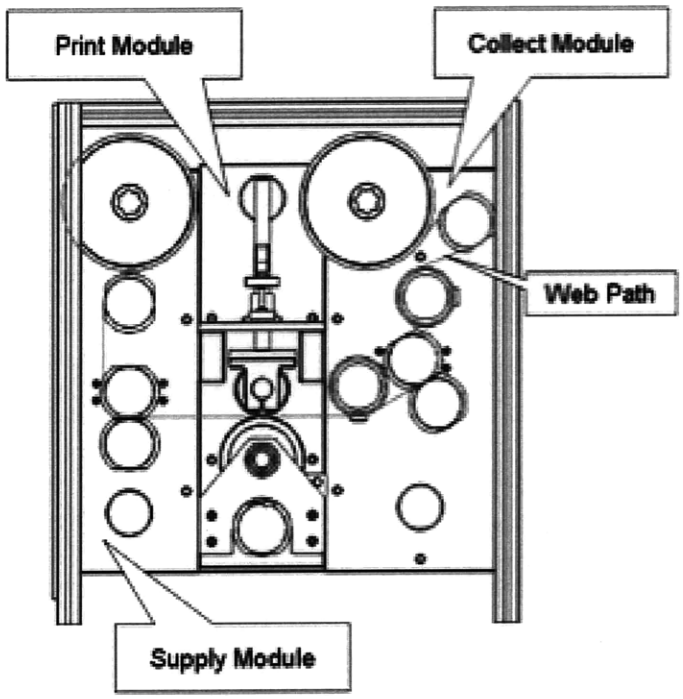


Figure 2.4 Layout of The Three Modules in The Equipment [4]

We shall not describe the operation of the machine in much detail, but will emphasize on the results of the print module only, as this was felt to have the most significant impact on the results, which also have been described in detail later in this document.

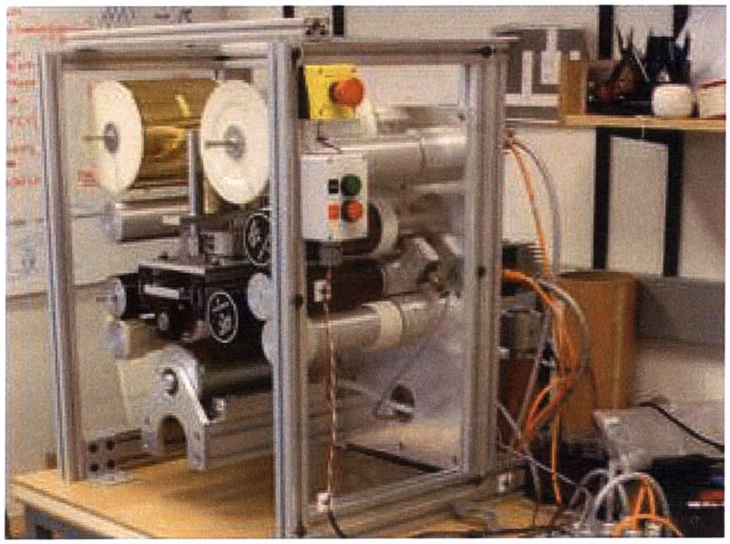


Figure 2.5 The R2R Machine Built in '08 [4]

A series of experiments were designed and conducted to test the printing quality. Below is a summary of relevant results [4].

1. Neither printing pressure nor speed was found to have a significant effect on spatial distortions and pattern dimensions in the range of settings we used.
2. It is possible to print a robust etch-resisting SAM at very high speeds (400 ft/min, unit area contact time ~ 5ms).
3. At very high speeds (400ft/min), some systematic air trapping was observed
4. The alignment of the stamp on the backing may have a significant effect on distortion patterns.

These results have formed the basis for our project. Improvements in the following were seen as critical to improving the printing quality:

Alignment of the stamp on the backing, and therefore on the print roller
Fabrication of a flat stamp
Precision in the web handling system of the equipment

2.4 Stamp Casting Machine

Stamp fabrication is essential to improve the quality of printing. Micro-contact printing requires precise transfer of patterns with minimum distortion and maximum yield. In addition, the stamp needs to maintain an exactly complementary pattern to the master, and it should avoid distortion during printing.

PDMS as the material for stamp has a low Young's modulus; therefore, under tension or external force, the PDMS will distort and result in a distorted pattern. In previous projects, PDMS has been cast onto a rigid backing plate. The backing plate is treated with a plasma and surface treat chemicals to increase its adhesion to PDMS, andthe force between this backing plate and PDMS is firm enough that little relative motion between the stamp and backing plate will happen. Thus, the backing plate with PDMS minimizes distortion when wrapping the stamp onto the print roller.

With the consideration of cost and efficiency, large stamps are desired for production. In common practice, round wafers (150mm, 200mm and 300mm size) are used as the master and etched out negative pattern on the SU-8 layer on the master. This photo-resist will directly contact PDMS during the practice, thus caution should be made in order not to destroy the pattern on the master. The size of the stamp is limited by the size of wafer. In this project we targeted 300mm wafer as our master and explored the problems including distortion, uniformity, peeling force from master and repeatability with the capability of scaling in manufacturing.

In previous research at Nano-Terra LLC, the thickness of the stamp was shown to affects the pattern transfer and a thin stamp seems to result in better printing quality. This research is not restricted to self-assembly monolayer printing, For applications in which pressure is critical to the quality and yield of printing, the elasticity property of the stamp will be key consideration and this property is directly affected by the thickness of stamp. A uniform, thin layer of stamp is beneficial to other on-going projects in the soft lithography.

Nano-Terra developed their first casting machine (see Figure 2.6) using aluminum with a 12" master, which demonstrated capability of large area stamp fabrication. In figure 2.6, a vacuum chuck at the left hold the backing plate and flips onto the wafer chuck at the right where the wafer sits. PDMS is injected into the gap between backing plate and wafer.

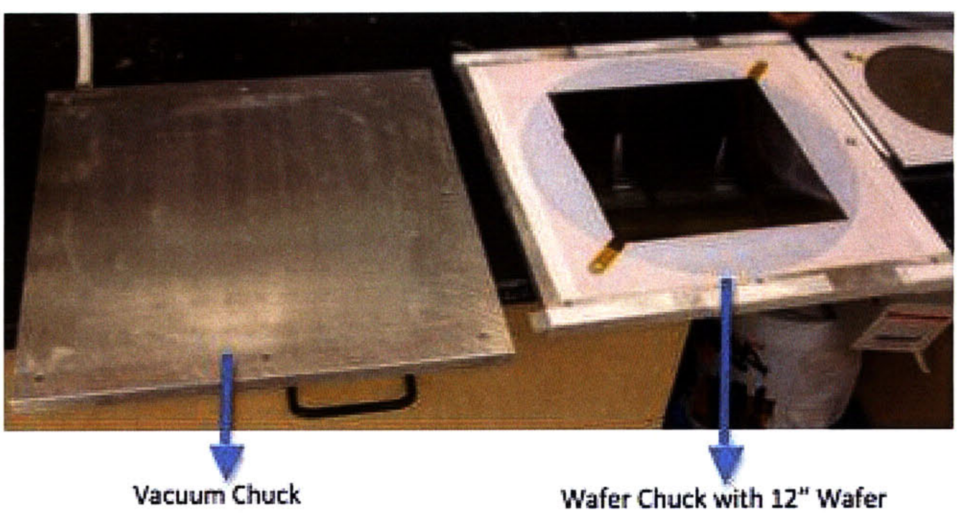


Figure 2.6 Main Parts of Aluminum Casting Machine for Large Area Stamp, Developed by Nano-Terra LLC.

As shown in figure 2.6, this configuration is to have two vacuum chucks : one attaching the master and the other attaching the backing plate. A dam (or reservoir) is placed around the area. These two chucks face each other, and create a space, which is circled by the dam. Liquid PDMS is injected into the area with a syringe.

This pilot stamp fabrication equipment demonstrated consistent quality for use in large size stamp. However it is not designed for interchangeable masters because its mechanism for fixing the master does not allow quick uninstall. Also the space between backing and can't be adjusted easily. Thus it was not able to experiment for manufacturing purpose. Surface finish of the vacuum chuck is rough, which results in uniformed thickness across the stamp.

To resolve these problems identified from this pilot PDMS casting machine, a better material that is capable of ultra-high precision machining is necessary. The Wafer chuck will be modified to add-in alignment capability for maintaining repeatability each time a new master is brought in. Thickness of stamp can be varied by changing the spacing part between wafer and backing plate. This is the topic of Yufei Zhu's thesis [24], detail explanation on stamp fabrication process could be found in his thesis.

2.5 PDMS Peeling Process

The peeling process is a crucial step where we need to wrap a PDM stamp, which initially lies flat on a Silicon wafer, onto the print roller. Thus, it is essential to first successfully peel the PDMS stamp without any tears or distortions. This section studies some of the research that has been done on peeling PDMS off Silicon wafer.

2.5.1 Stress Zones at PDMS Peel-Front

Considerable research has been done on peeling PDMS off a Silicon wafer. However, the upper side of PDMS is not attached to any other surface (like a metal plate), but is open to air. In our project, the topside of PDMS is attached to a steel backing plate. However, some of the findings of the research are indeed useful despite this difference, and are as below.

In general, at the peel front, boundary conditions are different on the two sides of the PDMS stamp; in fact, on one side, the surface of the film has zero shear stress (or very small shear stress, in our case) because it is not attached any surface (or to a different surface), while on the other side, the film adheres to the silicon master and shear stress is imposed on it by the substrate. This configuration creates a singularity around the peel front. This very small and thin zone is characterized by a highly variable stress values. This stress singularity in the normal direction causes the separation of the film at the peel-front.

When viewed closely to the peel front, peeling of PDMS could be schematized as below:

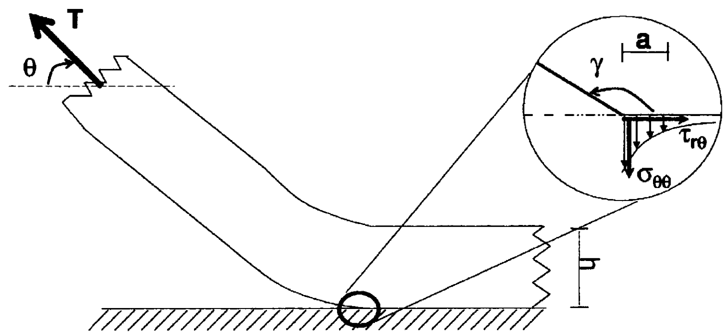


Figure 2.7 Illustration of separation at the PDMS-Silicon wafer boundary [22]

2.5.2 Initiating Peeling

Generally, to initiate the peeling operation we need apply a force at the peeling front, and as shown in figure 2.8, this force can be applied either, A: an upward force on the top surface of the film or B: a force applied at the edge on the bottom surface.

Previous works showed that, the success of either approach depends on how close the applied force is to the vertical plane of the peel-front. Only when the force is applied in the same vertical plane as the edge, the singularity at the edge results in peel-initiation.

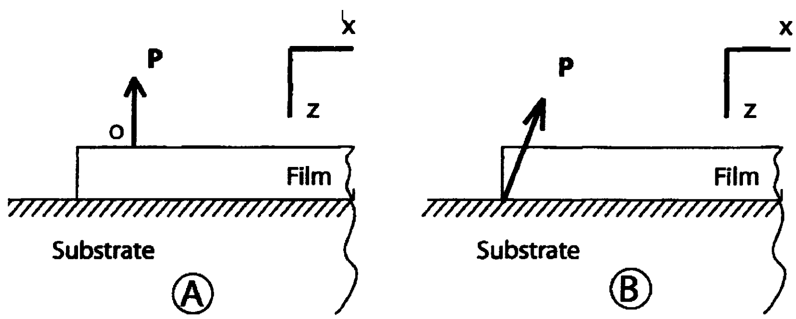


Figure 2.8 Directions of peeling force [22]

2.6 Multi-Layer Printing

After the successful demonstration of high throughput and good yield in one-layer printing using R2R machine, our background knowledge is sufficient to start the research in micro-contact printing's capability of multi-layer printing. This is an important step towards the actual application in manufacturing because micro-contact printing is no longer limited to printing of photo-resistive material as the ink. Further applications require multiple layers to overlap to achieve complex function. The units under consideration include diodes and transistors with at least 3 layers.

An important specification introduced in multi-layer printing is accuracy in relative layer position or registration. We are expecting to achieve registration with the roll-to-roll structure, because of the high throughput. However most literature discusses methods to align surface to surface, including the alignment between mask and wafer in semiconductor industry, or dip and substrate in inkjet printing, while few have mentioned alignment issue between round subject and flat substrate. Thus references for designing machine capable of multi-layer printing will be mainly from color printing industry.

It is common practice to start building high precision system based on an open-loop structure and to add-in close loop component to increase the accuracy. An open-loop structure is simple because micro-contact printing requires only two motions: linear motion of substrate and rotational motion of the print roller. Since roll-to-roll machines are widely used in printing industry, it is beneficial to learn how the feedback systems work. We will use gravure printing to demonstrate how the printing industry achieves this registration. Figure 2.9 shows a typical gravure-printing machine.

Figure 2.9 Gravure Printing Machine.

Gravure is widely used in high quality printing. Because human eyes are not sensitive to features less than 40 micron wide, the feedback system for gravure machines usually set the accuracy at 100 micron or less. Errors in two key directions have been compensated. One is the direction of substrate motion during printing, or the "path"; the other is the direction perpendicular to the path on substrate plate. The latter is easy to adjust by moving roller along its axis; the error in path is sensed and compensated using sleeve displacement between the roller and the sleeve (see figure 2.10).

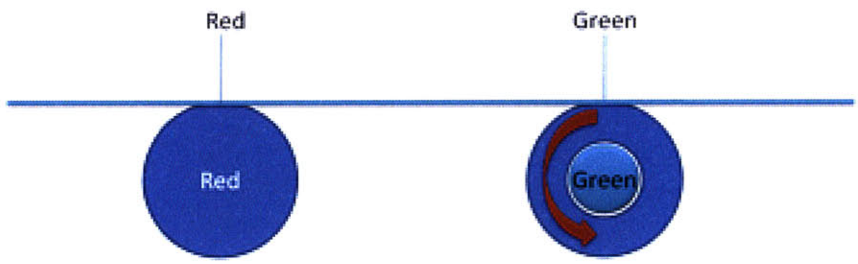


Figure 2.10 Actuation Method For Adjusting The Relative Distance Between Print Nips on The Substrate.

In Gravure printing, marks are printed with a distance of 20mm, and individual roller prints each color mark. Sensors are used to check the distance between marks to determine the relative position between different colors on substrate. The sensor system is shown in figure 2.11. The signal from sensors are received only when designated color are about to arrive. Once an error is detected, the controller will send out signals to the roller whose color is offset from its desired position, and the sleeve on the roller will rotate to compensate for this error.

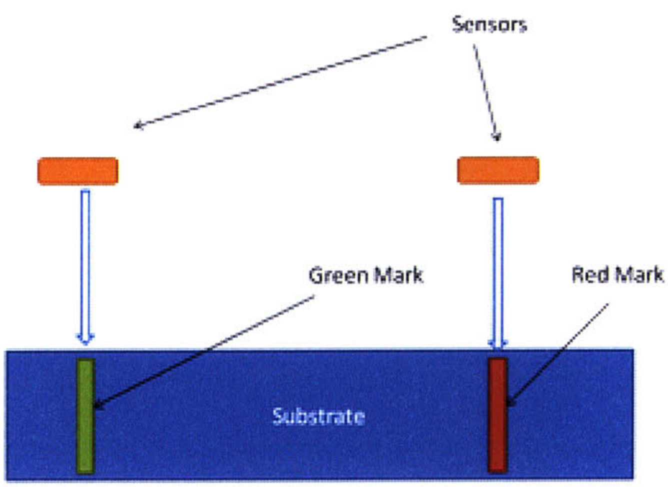


Figure 2.11 Simplified Sensing Method For Detecting The Relative Position Between Two Layers of Print in Gravure Printing.

Assume both red and green rollers are rolling at the same speed, the green and red mark on the substrate will have a constant distance of 20mm, and signals from both sensors will reach controller at the same time. If, however the green roller is one step behind compared to the red roller, the green mark will shift back at some distance, and a signal from the green sensor will lag from the red signal. The controller will determine the amount of offset from the time of this lag and control the sleeve on green roller to shift one step ahead.

2.7 Optical Methodology System Review

One of the objectives of the project is to fabricate the stamp within the variance of ±4μ, which means high precision measurement tools has to be employed. Currently, there are various kinds measurement sensors that can achieve very high accuracy and resolution, but they also have specifications that match some specific needs. In this section, laser triangulation sensors, interferometers, fiber optic sensors and con-focal microscopy are reviewed as our potential choice of measurement sensors.

2.7.1 Laser Triangulation Sensors

Triangulation measurement is an old but very useful method to measure distance. Laser sensor is a powerful tool, using triangulation measurement, to measure either long-distance or short-distance with high accuracy. However, the long distance measurement may not provide very high resolution. Laser sensor projects a spot of light onto the target and receives the reflected light with photo detector through an optical lens. A typical laser triangulation system is shown in Figure 2.12 below.

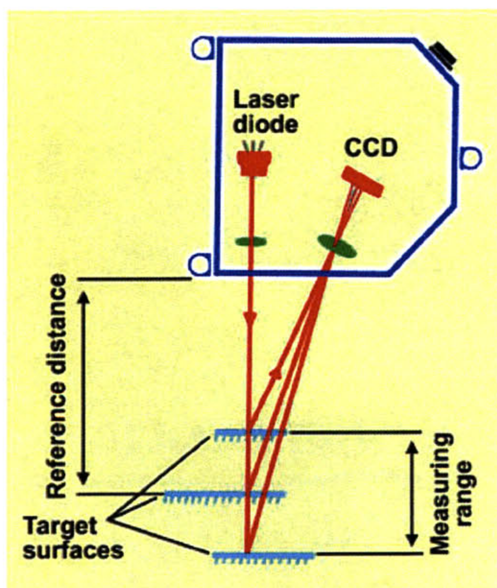


Figure 2.12 Principal of Laser Triangulation Sensor [14]

From the figure 2.12, we could see that the relative position of laser diode, lens, photo detector and the position of reflected light from the target on the photo detector determine the distance of the target. If the target changes it position, the reflected the light changes its position on photo detector as well. Through linearization and additional digital or analogue signal processing, the detector could provide an output signal proportional to the position of the target. The ambient light has little effect on reading, because the signal is proportional to the center of intensity of focused image [14].

The most important part of laser sensor is the photo detector, which could be photo diode, position sensitive device (PSD), charge coupled device (CCD), Complementary metal–oxide–semiconductor (CMOS), etc[14]. Different photo detector requires different signal processing method.

The following summary of general laser triangulation sensors' characteristics is built upon the works done by Alexander H. Slocum in his book named *Precision Machine Design* [16], updated with recent industry standards. Note that the manufacturers are always advancing the state-of-art, so this summary is generalization only.

Size: Typically 30x50x70mm

Cost: Depends on the resolution. Normally, 1 μ resolution laser sensor cost $4000.

Measurement Range (span): 3 - 1300mm

Accuracy (linearity): 0.03% of Span, 500 Hz, to white target (85% diffuse reflectance)

Repeatability: Depends on the repeatability of the surface finish.

Resolution: on the order of 0.005% of full-scale range, could achieve as high as 0.1μ

Laser spot size: 30-300μm

Environment Effect on Accuracy: On the order of 0.01%/^{0}C of full-scale range from the nominal 20^{0}C operating temperature

Power: 15 – 24 Volts DC, 120 – 200 mA draw with 350 mA surge at power-up

Allowable Operating Environment: Keep optical windows clean for best performance. System typically operate from 0 to 40 ^{0}C

2.7.2 Interferometer Sensors

Various kinds of interferometers are in use today. Michelson interferometer has the most common configuration for optical Interferometry and was invented by Albert Abraham Michelson. A typical and simplified interferometer system is shown schematically in Figure 2.13.

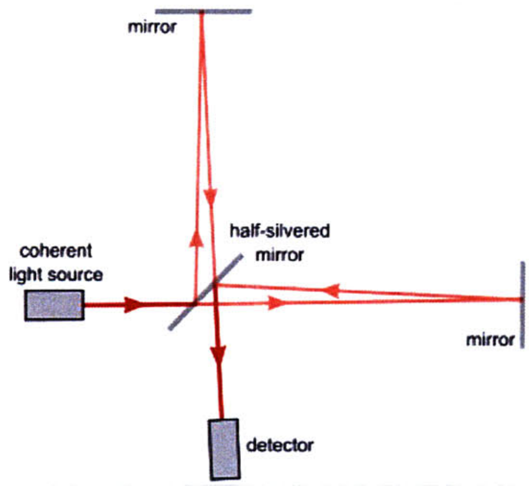


Figure 2.13 Principal of Interferometer System [15]

According to figure 2.16, a continuous light source was spitted into two paths: One bounces back from the semi-transparent mirror, and then reflects back from the mirror on the top, goes through the semi-transparent mirror, to the detector. The other one goes through the semi-transparent mirror, bounces back from the mirror at right, and then reflects back by the same semi-transparent mirror and goes into the detector. Difference in path may result from the length difference or different materials, which cause alternating pattern on the detector. If no difference of materials involved in the interference, the distance could be measured through

The following summary of general laser triangulation sensors' characteristics is built upon the works done by Alexander H. Slocum in his book named *Precision Machine Design* [16], updated with recent industry standards. Note that the manufacturers are always advancing the state-of-art, so this summary is generalization only. It is also extremely important to stress that the accuracy of measurement is highly depended to the manner of how the optics are mounted and how the environment are controlled.

Size: Laser head, 130x180x530mm.

Cost: About $9000 for laser head and electronics boxes for up to 4 axes of measurement.

Measurement Range (span): up to 30m[16]

Accuracy: In a vacuum, if perfectly aligned, the accuracy can be on the order of half (worse) the resolution. As for non-vacuum conditions, the environment significantly impacts the accuracy of measurement.

Repeatability: Depends on the stability of the environment and the laser head.

Resolution: Depends on optic used and can be achieved as high as $\lambda/4096$. Higher resolution could be achieved through better optics and phase measurement technique involved.

Environment Effect on Accuracy: About 1μm/m/^{0}C Air turbulence and thermal expansion of optics, mounts and the machine itself [16].

Power: 12 V, 200 mA (PICO M8 con.)

Allowable Operating Environment: Since the interferometer is sensitive to the environment, ideally, it should be used in a vacuum, or in air of 20^{0}C with no gradients.

2.7.3 Fiber Optic Sensors

Optical fibers are glass or plastic fibers that transmit light using the property of total internal reflection and the fiber act as waveguide [25]. Figure 2.14 demonstrates the total internal reflection of a laser inside the optical fiber.

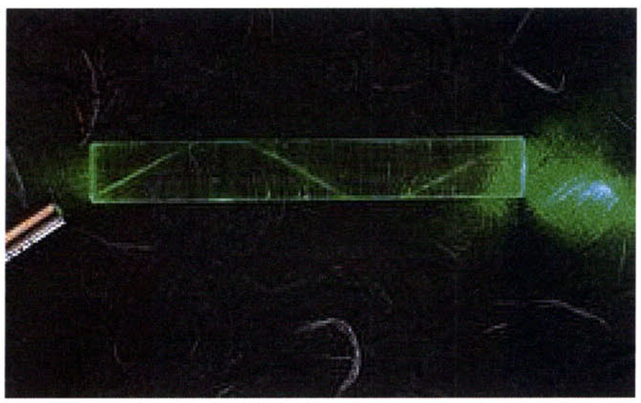


Figure 2.14 Total Internal Reflection inside Optical Fiber. [25]

The key elements for fiber optic sensor are two sets of flexible probes: one is for transmitting and the other is for receiving. Two probes are jacketed into one to measure the distance. There are basically three kinds of probes configurations: Hemisphere, Random and concentric, as shown in Figure 2.15. Active diameter of probes could be as small as 0.177mm, making them ideal to measure small target [17].

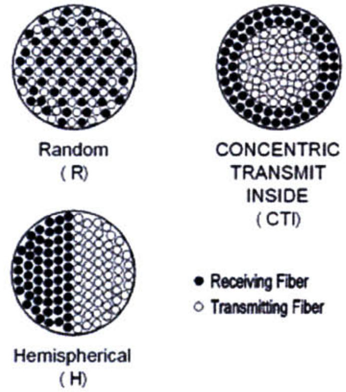


Figure 2.15 Fiber Optic Probe Configuration [17]

The distance of an object can be determined based on the intensity of reflected light that is sensed by two transmitting and receiving fiber probes [18]. The response curve is shown in Figure 2.16, and the intensity of reflected light is converted to voltage output. Optic Fibers are not sensitive to electromagnetic interference and typically very light [16].

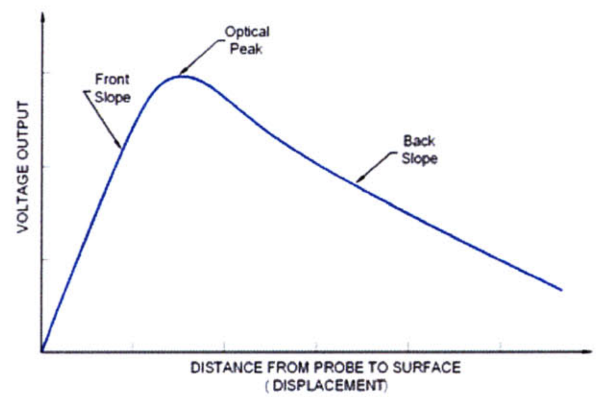


Figure 2.16 Fiber Optic Probe Response Curve [17]

The following summary of general laser triangulation sensors' characteristics is built upon the works done by Alexander H. Slocum in his book named *Precision Machine Design* [16], updated with recent industry standards. Note that the manufacturers are always advancing the state-of-art, so this summary is generalization only.

Size: cable diameter could be 1mm or even smaller

Cost: Depends on the type of sensor, \$100-\$1000.

Measurement Range (span): a few millimeters for small displacement (<10mm)

Accuracy: 0.1% of full range;

Repeatability: Depends on environment conditions

Resolution: Can achieve very high resolution if the sensor held very close to the target, like 0.01μm resolution with the range of 0.1mm

Environment Effect on Accuracy: very sensitive to environment, like dirt on the sensor will degrade the performance.

Allowable Operating Environment: Since the interferometer is sensitive to the environment, the sensing surface must be kept very clean. Individual probes should be kept away from moisture, or they will eventually erode to the point of failure.

2.7.4 Con-Focal Laser Scanning Microscopy

Con-focal laser scanning microscopy (CLSM or LSCM) is a technique that could capture very sharp optical images at selected height [23]. A very important feature of con-focal microscopy is that it could obtain images from various depths. Because of its high resolution on depth measurement, the con-focal microscopy could be applied to measure the flatness of object within the limitation of the measurement tool.

In con-focal laser scanning microscopy, a coherent light source projects a beam of laser, which goes through the beam splitter and focused on the target via lens. Scattered and reflected laser light, together with the illumination light, were re-collected by the lens and then focus on the detector via the reflection of the same beam splitter. The aperture of detector blocks the light that is not from the focal point and hence leads to a sharper image comparing to conventional microscopy. (See figure 2.17)

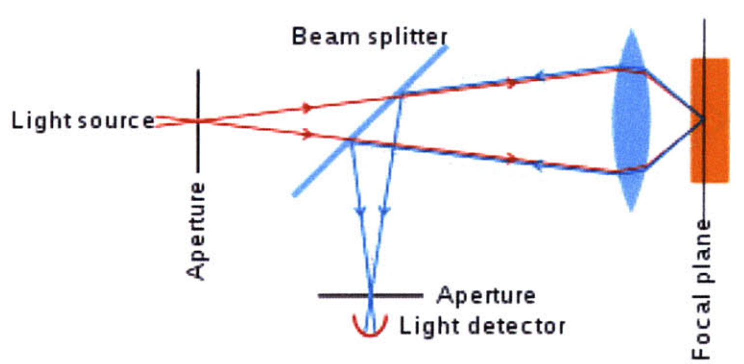


Figure 2.17 Principal of Con-Focal Microscopy [23]

Adjusting the position of lens could allow light detector capture the sharpest image of the targeted area. Most of current con-focal measurement systems are using CCD to detect the target and measure its position.

In this project we are using Nikon VERITAS VM250 as our main metrology to test the surface flatness through measuring the depth of the sample points. The following is the summary of general characteristics of Nikon VERITAS product series.

Size: Main body - 565 x 690 x 740 mm (minimum height), 72kg; Controller - 145 x 400 x 390 mm, 13kg

Cost: Depends on the type the precision and measurement range, more than $10,000

Measurement Range (span): could achieve 50mm

Accuracy: could achieve 1 μm

Repeatability: rely on xyz moving stages

Resolution: Can achieve 0.1μm

Power: AC100-240V±10%, 50/60Hz

Environment Effect on Accuracy: within allowable operating environment, the accuracy can be well maintained

Allowable Operating Environment: Temperature - 10°C to 35°C; Humidity - 70% or less

3. Methodology

3.1 Stamp Casting Machine

Before processing the casting machine compatible with 12" master, we started with a 6" casting machine to see the capability of the design and building material (316 Stainless Steel). The design allows both 150mm wafer and 200mm wafer to be used in the same configuration. The stamp-casting machine will be capable of alignment for different masters. We use pins to locate wafer. In order to hold tight the wafer during pouring PDMS, grooves are designed for vacuum capability and wafer will be held using vacuum after aligning (see figure 3.1). Because no glue or tape will be used in the process, wafer will be easily replaced once the vacuum has been turned off.

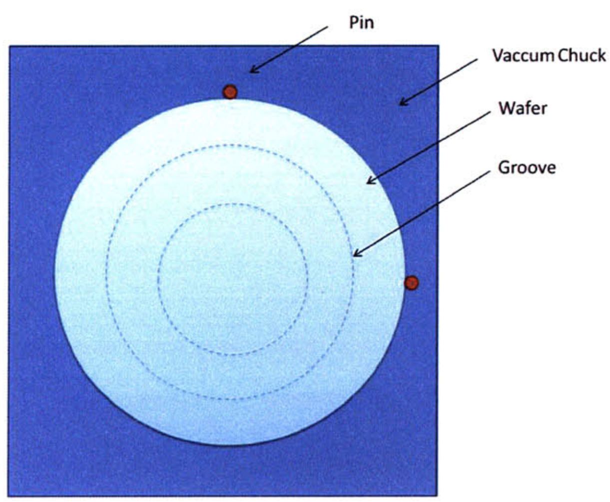


Figure 3.1 Structure for Wafer Chuck

A single piece of Teflon with a rectangular opening inside will attach to master as the dam for holding PDMS within the area, this Teflon will also act as spacer between master and backing plate (see figure 3.2). Shape and the thickness of the stamp on the backing plate are determined by this Teflon.

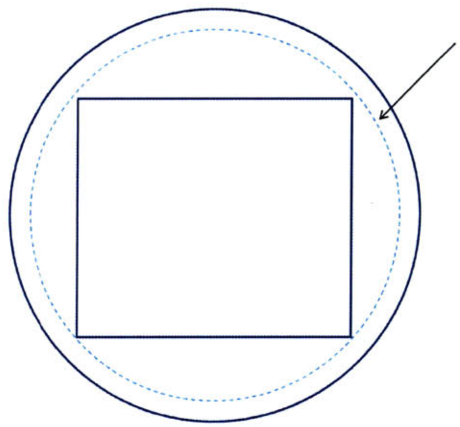


Figure 3.2 Teflon Spacer

The area for containing PDMS is confined by:

1. Wafer on the top for transferring pattern;
2. Thin stainless steel sheet (backing plate) sitting at the bottom as the backing for PDMS;
3. Dam between wafer and backing plate for holding the PDMS.

Repeatability is the critical design specification. Under this configuration, making a single big stamp will require many identical steps, and each step will result in a small area of finished stamp. Variables to be considered are:

1. Distance between master and backing plate (all attached to the chuck)
2. Displacement between master and backing plate
3. Uniformity of the stamp

All these variables can be decomposed in 6 dimensions: 3 linear and 3 rotational.

A sidebar is used to align both chucks, as shown in figure 3.3. The backing plate chuck (referred as SS Vacuum Chuck) is fixed to the side bar, while the adjunction of wafer chuck and sidebar leaves some clearance for adjusting. Minor adjustment is done by using screws to locate wafer chuck in both X and Y directions. The Z direction, also determines the height for stamp, is fixed by the thickness of dam.

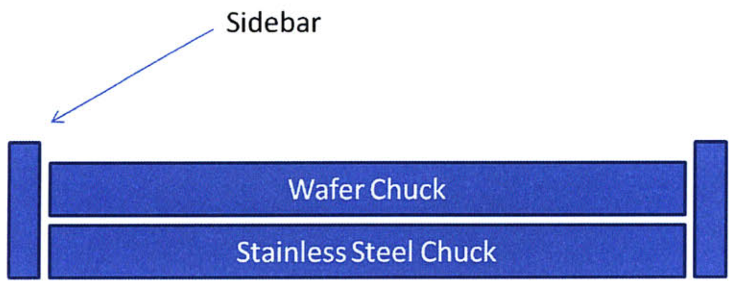


Figure 3.3 Sidebars Used to Align Both Chucks

Because the fabrication of stamp from PDMS is done in a low-pressure environment, the chucks with dam inside will be clamped together with strong force to ensure no air leaks in. Traditional C-clamp does not fit here because point contact will create distortion. Our approach needs to distribute the force as uniformly as possible. A clamping bar connected to sidebar by screw is used to provide clamping force. Small precision springs will be inserted between the clamping bar and wafer chuck to apply equal force.

3.2 Peeling and Wrapping the Stamp on the Print Roller

The R2R machine that was built by MIT'08 group proved that the R2R technique is feasible with micro-contact printing technology, but experiments showed that the printed images were affected by many distortions. The current way to wrap the PDMS stamp on the print roller is performed manually using a seam on the cylinder.

The challenges in the manual wrapping process using a seam demand the intervention of a skilled operator, making the process both time-consuming and labor-intensive. Also, even if all the operations will be performed in the correct way is not possible to guarantee the 5 microns alignment as required.

Therefore, the first goal of the project consists of improving the printing quality, designing a way to peel and wrap the stamp that will respect the following aspects:

- Maintain alignment
- Fast replacement

3.2.1 Gripping the Film for Peeling

The setup of the print roller before wrapping process is shown in figure 3.4. This setup comes after flat stamp fabrication process: dissembling the vacuum chuck from the fabrication device and placing the print roller at the edge of the backing plate.

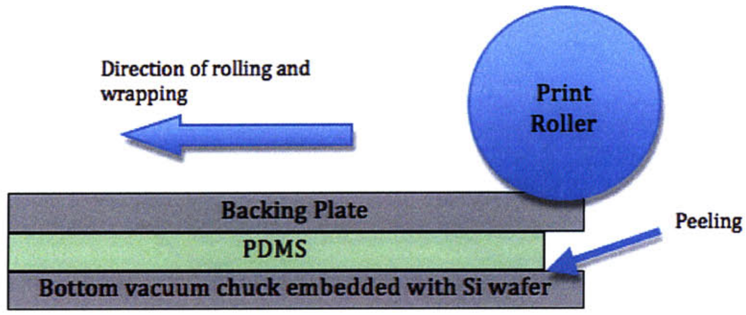


Figure 3.4 Illustration of Pint Roller Setup before Wrapping

Any device that grips the backing plate for peeling off the stamp must accomplish three steps in the peeling process:

1) Initiate the peel
2) Separate the film from the wafer
3) Transport the peeled film away

Unfortunately, the first and second stages are complicated by the inherent physics of peeling that we discussed in the literature review in the previous chapter. Let us begin by looking at the initiation of separation. This is a difficult step because the PDMS film adheres over the entire area of the substrate, leaving no 'lip' to hold the film or to start the separation. When an operator introduces a lip by inserting a razor, she must be careful not to scrape the film or inadvertently cut through it. Once she initiates separation, the operator may pull the film at point-contacts, which may cause excessive stresses and risk tearing around the contacts. If the film is adhered well to the substrate, she may need to pull hard on the PDMS film, which could also cause tearing.

Therefore, it is necessary to design a system that is able to grab and wrap at the same time the PDMS stamp that performs the following:

1. Grab the PDMS stamp without causing breaks or plastic deformations
2. Keep peeling the PDMS stamp applying a force with constant intensity, constant direction, and with a uniform distribution.
3. Wrap the PDMS stamp on the roller without loosing alignment and without causing relative motion between cylinder and backing plate.

Keeping in mind the above requirements, we designed and analyzed concepts for peeling and wrapping the PDMS onto the backing plate. These concepts have been summarized below.

It should be noted that, based on the results of the MIT '08 project, it is evident that this step of peeling and wrapping with precision and alignment is the most crucial step, in that it has a direct bearing on the printing quality.

3.2.2 Methods to Generate Adhesive Force between Backing Plate and Print Roller

Through the industrial investigation, we summarized the concepts, which are available on the market, to search for optimal solution the generate adhesive force between backing plate and the print roller:

1. *Electro magnet cylinder.*

It has ability to switch on and off the magnetic force of attraction, thus enabling better manual control over the pre-alignment of the print roller positioning with respect to backing plate.

However, the electro magnet cylinder requires additional electrical components and needs complex additions or modifications to print roller.

2. *Permanent magnetic cylinder.*

It could provide strong magnetic force, even if rare earth magnets used, which is easily available.

On the other hand, permanent magnetic cannot switch off magnetic force. Also to machine a cylinder with permanent magnetic force is expensive and difficult to obtain precision in diameter and tight tolerances.

3. *Cylinder with vacuum force*

The vacuum holes along the cylinder could provide uniformly distributed attraction force along surface of cylinder. The vacuum cylinder is adaptable from existing commercial vacuum rolls.

Nevertheless, the vacuum cylinder requires additional vacuum pump and vacuum control. And backing plate will have to cover entire vacuum-surface of cylinder; otherwise leakage of vacuum could be an issue.

4. *Cylinder with double sided adhesive tape on the surface*

Attaching the double-sided tape onto the surface of the cylinder could also provide strong adhesive force and such design is obviously simple and easy.

The disadvantage of this method is that the double-side tape Introduce another layer between the print roller and the backing plate which another source of variation on the roundness of the roller. In addition, it is difficult to correct errors of misalignment of backing plate with cylinder. Furthermore, cleaning cylinder for stamp replacement would be very difficult.

Chosen Method: Through analyzing above those possible solutions of the print roller, we finally decided to use stainless steel cylinder with a series of permanent magnets embedded into the cylinder. This kind of cylinder is a well-established design for use in the die-cutting and embossing industry, hence easily available. Also, this design satisfies all the precision and accuracy requirements with respect to the diameter, total run out, and straightness of the cylinder.

3.2.3 Methods to Wrap Backing Plate without Losing Alignment

1. Slot in print roller, clamp to grab backing plate

Clamp refers to an L shaped projection that would slip between the backing plate and the Si wafer. This would enable a positive grabbing or locking of the backing plate with the print roller, it requires pre-alignment before clamping.

2. Slot in print roller, bent edge of backing plate

This would be similar to using a clamp, except that the backing plate would be bent, and would stick out, enabling one to insert the bent edge into a slot in the print roller, again accomplishing a positive locking arrangement. But the relative position of the edge of backing plate and the slot has to be very accurate in order to maintain the alignment.

4. Pins in roller, holes in backing plate

This design consists of two (or more) pins inserted using threaded holes in the body of the cylinder. Corresponding holes would be drilled or machined in the backing plate. The height of the pins sticking out of the cylinder would be less than the thickness of the PDMS (less than 500 microns). This would prevent damage to the wafer during peeling and to the substrate during printing. Also the pins and holes could provide enough assembly constrains to guarantee desired alignment.

Chosen Method: Pins in roller, and holes in backing plate. This was found to be the simplest, easiest to adapt, and the most precise design.

3.2.4 Analysis of Fixture System

A fixture system that helps to guide the movement of the print roller during the wrapping was designed, as shown in figure 3.5.

The fixture would serve two purposes:

1. Pre align cylinder with backing plate

2. Maintain alignment during wrapping of the backing plate on the cylinder

However, the fixture system over constrains the cylinder-backing plate during wrapping. This is because, the force of adhesion between the cylinder and backing plate already achieves alignment between the two. Hence, if the fixtures try to achieve a slightly different alignment, it would create distortions and twisting forces in the backing plate, which would lead to detrimental effects on the stamp, and induce unwanted stresses in the stamp.

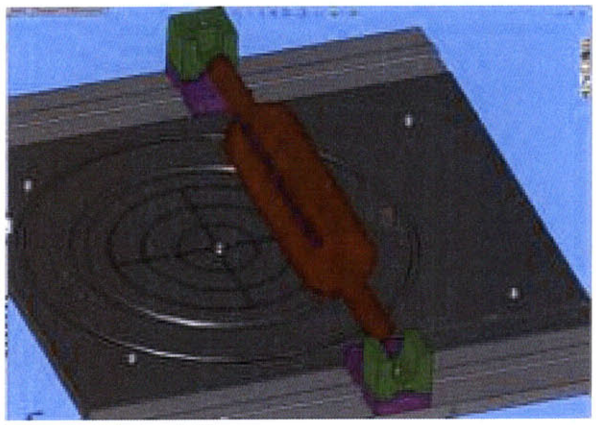


Figure 3.5 Illustration of The Proposed Fixture System

Upon conducting experiments with a prototype Aluminum cylinder, with pins, and holes on backing plate, and conducting error analysis for the same, it was decided that pin-holes are the best way to minimize alignment errors between the backing plate and print roller. Thus, the fixture system was not used.

3.3 Precision Measurement Method

The initial purposes of this project were to fabricate a stamp with uniform thickness, wrap the stamp onto the roller with uniform roundness and to demonstrate multi-layer printing. In order to answer the questions like how thick the stamp is, how flat the stamp is, how good the quality of multi-layer printing is and etc., a thorough measurement method need to be develop to precisely and correctly answer those questions. Meanwhile, multi-layer printing requires upgrading the accuracy of alignment of the current R2R system, so a systematical measurement is also desired to demonstrate the improvement of alignment in accuracy.

3.3.1 Flatness and Roundness Measurement

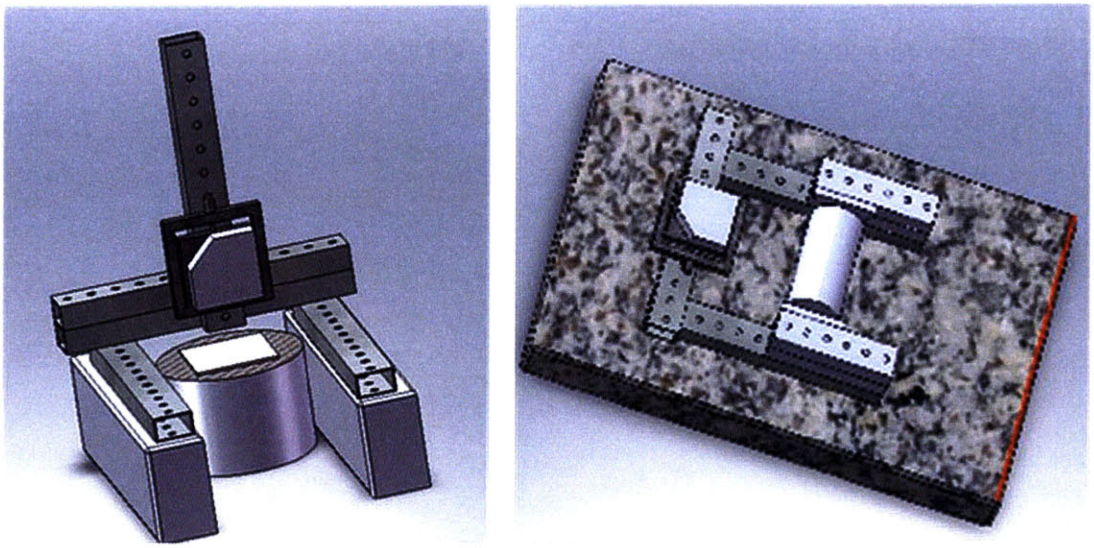
In the stamp fabrication and wrapping process, the ultimate goal is to make sure that the diameter of print roller has the variance of ±4μm, and the print roller here means the assembly of the central shaft, sleeve, and the backing plate with the stamp. All the potential variance could be broken down into following categories:

- Flatness measurement
    - Flatness of stainless steel.
    - Flatness of the PDMS stamp.
    - Uniform thickness of attached PDMS on stainless steel.
    - Flatness of devices that are used to fabricate the stamp.
- Roundness measurement
    - Roundness of print roller.
    - Roundness of central shaft.
    - Eccentricity of the motion of the driver motor.

Due to the specific characteristic of PDMS and the overall process, the measurement device should obtain following requirements:

- Non-contact measurement
- High resolution, targeting on 1μm
- Enough measurement range (>1mm)
- Affordable

At first, Laser triangulation sensor was the first choice, which is perfect aligned with all above requirements. Corresponding fixtures and frames were developed for the flatness and roundness testing, as illustrated in Figure 3.6. Basically, the laser sensor sits on the micrometer head for the fine adjustment and the micrometer head is mounted onto the frame to test either flat or round surface.



Flatness measurement Roundness measurement

Figure 3.6 Fixtures for Flatness and Roundness Measurement

However, the chosen laser sensor cost more than $4000 and could only be used for this project in the view of Nano Terra LLC, which is not cost effective for the company in sake of the future application. Therefore, we plan to use the available CNC Video Measuring Systems (Nikon VERITAS VM 250) that could measure the height of the surface by using con-focal technology. (The machine is shown in figure 3.7)

Figure 3.7 VERITAS VM 250

To measure the flatness using Veritas, the object should be placed onto the x-y stage and measure the height of sample points on the surface of the object. Since the x-y stage could move alone x and y axis in a perfect flat surface, it help to keep away from the disturbance introduced by the measurement equipment.

Roundness of the print roller is targeted because of its critical impact towards the printing quality. Although the roundness of print roller is very forgiving in self-assembly materials and the impression roller, which contacts the print roller during the printing process, could tolerate the variance of the roundness, the high roundness print roller is still desired in the view of future development. Because, if using some other materials that do not have self-assembly characteristics or very little pressure could be applied onto the print roller, a perfect roundness print roller is highly important to the final print quality.

In actual measurement, there is a problem about the roundness test due to the property of PDMS. PDMS is elastic transparent material that could not allow the laser sensor or the dial indicator to precisely measure the roundness variance. A few solutions could be applied to solve this issue: Interferometer is not limited by such kind of materials but it is too expensive for this project, or the stamp could be coated with metal powder and then use laser sensor to measure the distance, but this method will cause the damage of the stamp. Finally, the roundness of the printer roller could be indirectly indicated by the accumulate effect of the roundness of the print roller with the stainless steel sheet and the flatness of the stamp. The stamp is seamless attached to the stainless steel sheet; therefore, we assume the variance caused by the attachment is zero.

In the roundness test, since we are only interested in how round the print roller is when it is rolling for printing and try to compare the different performance of two wrapping systems, the measurement is took separately into two systems (previous R2R system and updated R2R system) while simulating a real printing process. The final roundness information of the print roller is the aggregated result of the motor shaft eccentricity, motion transition quality of the connected bearings, roundness of the central shaft, roundness of the sleeve, variance caused by assembling the sleeve on the shaft, firmness of the attachment between the stainless steel sheet and the sleeve, and the flatness of the stamp. The dial indicator is applied in this measurement and figure 3.8 illustrates the general idea of the measurement settings.

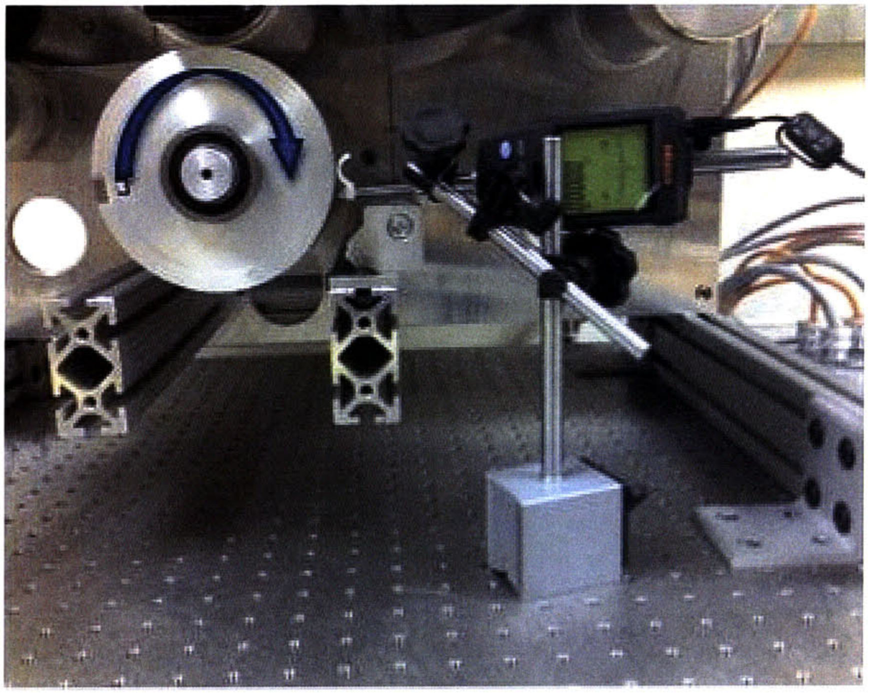


Figure 3.8 Measurement Setting for Roundness Measurement

With each rotation of the print roller, 16 sample points of are collected, 3 positions along the roller (Front, Middle and Back) are test, which means 16x3 sample points are collected for roundness analysis.

3.3.2 Distortion Measurement

After the features are successfully transferred from the stamp to the substrate (gold coated PET is the substrate used in this project), one of the most important quality indicators is the distortion of pixel on the substrate. The distortion is caused by several reasons:

1. The distortion of the flat stamp during the fabrication process.
2. The distortion caused by wrapping the stamp onto the print roller.
3. The tension of the substrate causing stretch of the feature.
4. The print pressure slightly deforms the features on the stamp.
5. Other noises.

All above sources of the distortion had been carefully analyzed in the thesis of *Analysis of the Capabilities of Continuous High-Speed Micro-contact Printing*[20] *by* Kanika Khanna. Based on her study, the wrapping process contributes the most to the final distortion.

The overall pattern printed comprises two types of pixel patterns, rectangular and triangular, as shown in Figs 3.9 and 3.10. The array of both of the these pixel patterns is shown in figure 3.11, where each pattern is printed on a 1.5mmx1.5mm square[20].

Figure 3.9 The Shape of Rectangular- like Pixel

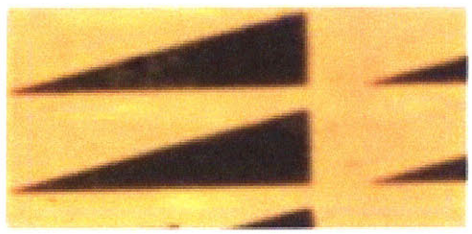


Figure 3.10 The Shape of Triangular Pixel

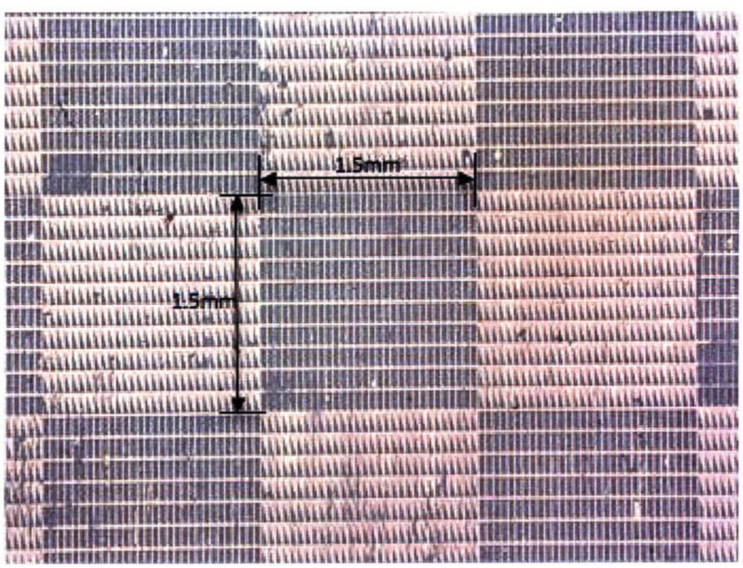


Figure 3.11 The Array of Two Kinds of Pixels

As mentioned before, the wrapping process causes distortion of the stainless steel sheet, which is used to hold the stamp in the printing process. The distortion of the stainless steel sheet leads to distortion of stamp, and hence the distortion of pixels. Figure 3.12 demonstrates the distortion of pixel in a simply way. The black dashed rectangle is the standard shape of the pixel on the substrate and the blue solid rectangle is the distorted printed pixel. In figure 3.12, X and Y indicate the horizontal and vertical dimension of the standard pixel; X' and Y' indicate the corresponding dimension of printed pixel. It is important to note that the shape of distortion varies based on multiple reasons. To indicate the distortion, we will just simply use Y'/Y and X'/X as the distortion rate to identify the distortion over the Y and X axis.

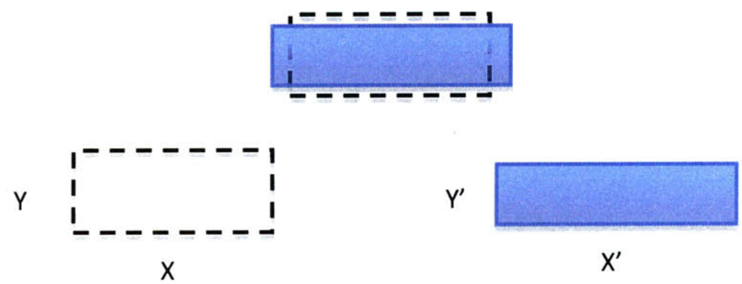


Figure 3.12 Demonstration of the Distortion

In order to make things easy, the distortion measurement is only taken on the rectangular-like pixels shown in figure 3.9, which is statistically representative to the overall distortion. For those rectangular-like pixels, their standard dimension is 130μmx40μm AS shown in figure 3.13.

It is important to distinguish pixel distortion from pattern distortion. In this work we concentrate on distortions of at the pixel level, and are not concerned with overall pattern distortion caused by web movement or a non-parallel stamp on the roll. The stamp is made from a 300mm wafer, and the actual size of the square stamp is 200mmx200mm. This area is evenly divided into 5x5 cells with each cell being 40mmx40mm. Within each cell, 5 pixels are randomly picked to measure, and averages to minimize the measurement error. This average is used to represent the dimension of the pixels in this area.

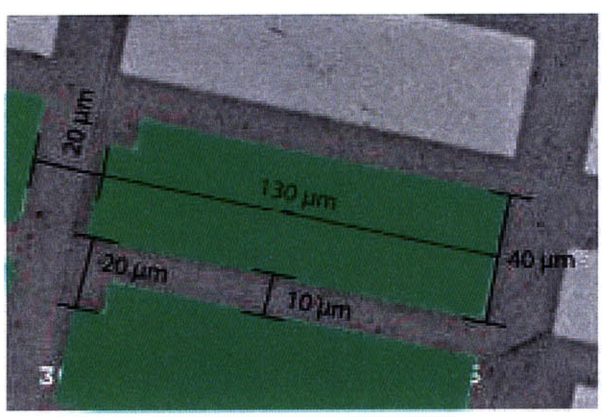


Figure 3.13 Pixel Dimensions [20]

3.3.3 Measurement of the Accuracy of the Alignment

The scope of the multi-layer printing in this project is to use the stamp print twice on the same substrate without loosing alignment. Therefore the accuracy of the alignment could be measured by indicating how well the overlap of two printed features, shown in figure 3.14. In current stage, only x and y displacement are concerned. The angular misalignment is not included in the measurement due to the time constrain.

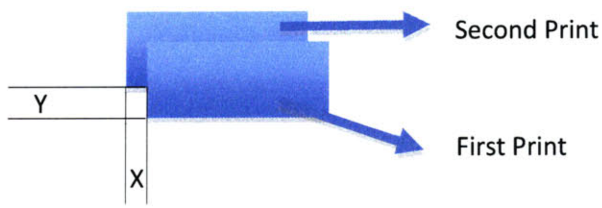


Figure 3.14 Displacement of Two Printed Layers

Same to the measurement of distortion, 5x5 matrix divided the 200mmx200mm printed area into 25 squares. Take the average of 4 measurement within each square for the x and y displacement.

4. Machine Design

4.1 Introduction

This chapter introduces the design process for all the hardware for updating the Roll to Roll machine. This work is divided into 3 parts:

1. Design and development of a new stamp casting machine,
2. Module upgrade of the roll to roll machine for multilayer printing capability,
3. Design of a multilayer printing machine for solid substrate printing.

For this work 3D models are mainly built with Solidworks. Most precision parts were machined by a local supplier. Some parts were sent to a specialized grinding company for grinding. Other components are machined in LMP workshop located in MIT.

As mentioned in Chapter 3, the quality of the stamp is essential to bring the printing quality of roll to roll machine to a higher level of performance. The new stamp casting machine is developed to cast a uniform stamp. Also with increased repeatability of the impression roller assembly, contact between stamp and substrate is easier to control. The stamp casting machine and revised roll to roll machine have been measured to quantify their design specifications. Several trials have been undertaken to perform multilayer printing, and all the trials follow the process described in this chapter. The results will be shown in chapter 5.

Nano-Terra Inc. was also considering building a multilayer printing machine capable of printing on solid substrate with high pressure. Included in the last section of this chapter are the analysis and preliminary design of a machine with functions required.

4.2 Stamp Casting Machine

The new stamp fabrication machine is a mature version of the old machine introduced in chapter 2. Improvements of this new design include:

- The pattern can be changed and self-aligned to wafer chuck;
- Flatness of the stamp is at the order of microns;
- The backing plate is mechanically aligned during stamp fabrication;
- Both chucks used in the machine can be disassembled to remove the PDMS stamp ;
- The machine is capable of maintaining low pressure (via vacuum) in the internal area when PDMS is poured in.

The critical parts of the machine are the wafer chuck and the stainless steel chuck (Figure 4.1). Because both wafer and backing contact directly to the chucks, the parallelism and surface level variance on the chucks determines the variance of thickness in stamp area.

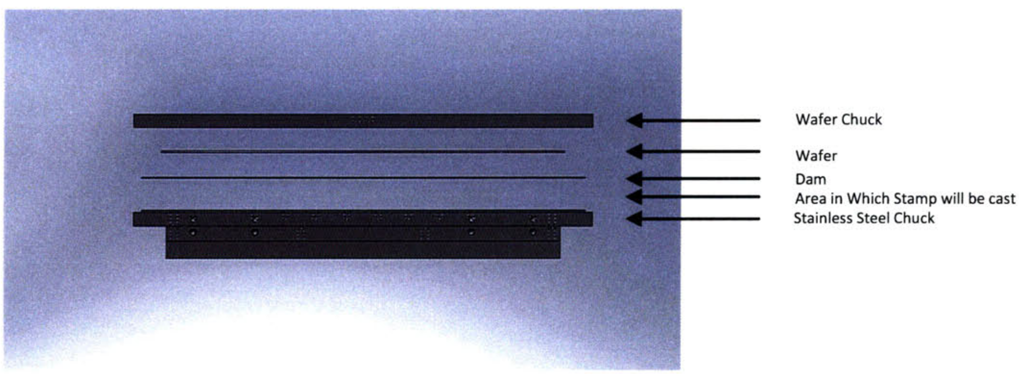


Figure 4.1 Schematic illustration of the casting machine

4.2.2 Wafer chuck

Wafer chucks (Figure 4.2) are used to hold the silicon wafers with a vacuum. The vacuum grooves on the wafer chuck are triangular. A wide circular tunnel is added outside the grooves to prevent PDMS from leaking into vacuum area below the wafer.

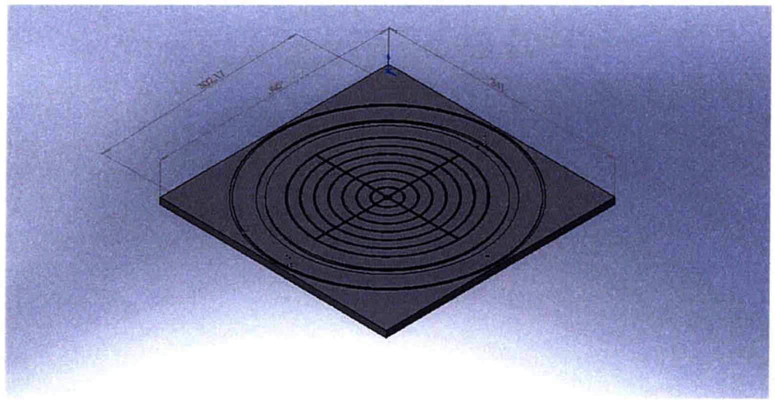


Figure 4.2 3D Model of Wafer chuck for 12" wafer

Pins are used to locate the wafer before vacuum is created. These features enable the wafer to align to the pins before being fixed by vacuum. In figure 4.3, the notch on wafer is aligned to Pin 1, and Pin 2 together with Pin1 fully constrains the wafer on the vacuum chuck.

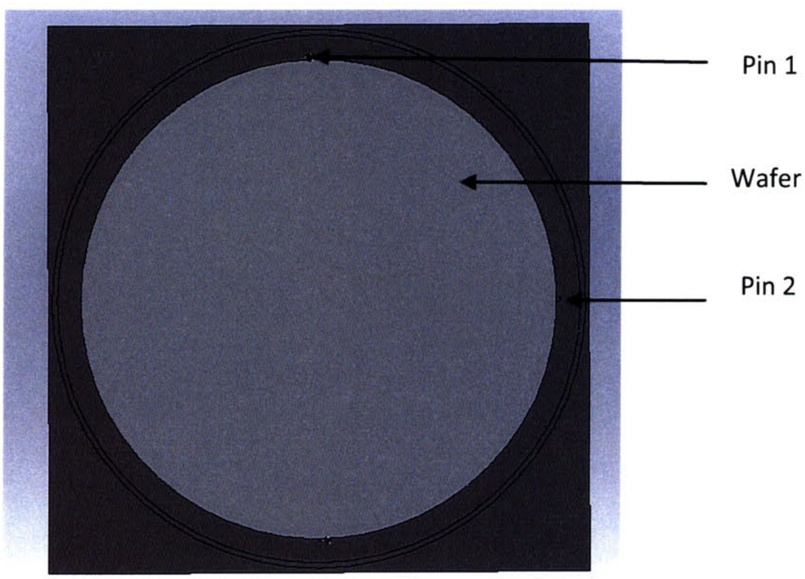


Figure 4.3 Location of Pins for wafer alignment

4.2.3 Stainless steel chuck

A stainless steel (SS) chuck (Figure 4.4) is used to hold the backing plate (also of Stainless Steel). PDMS will adhere to the backing plate, and wrap onto print roller after stamp is cast. The SS chuck is intentionally divided into several parts, allowing holes and vacuum channels to be cleaned whenever jammed by PDMS. In Figure 4.4, tunnels for vacuum are below the holes on upper part. The two parts are assembled with screws and can be dissembled easily. There are 10 by 11 holes on the surface creating uniform adherent force to the backing plate when vacuum is on.

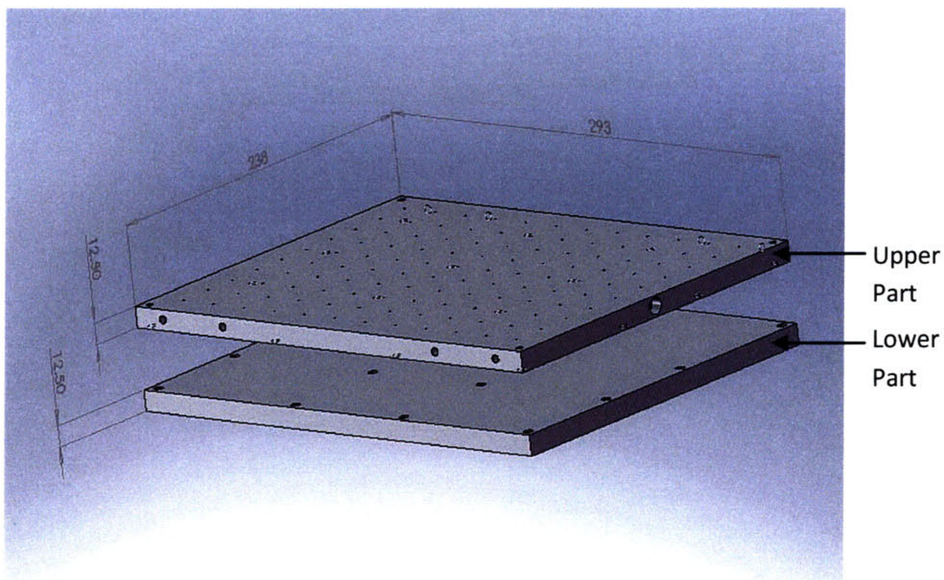


Figure 4.4 SS backing plate chuck model exploded view. This chuck is capable of producing stamps from 6" and 8" wafer.

An adapter (Figure 4.5) is used to hold a larger backing plate on which a 200mm by 200mm stamp will be cast (12" wafer).This adapter sits on top of SS chuck in Figure 4.3 Only the area where stamp will be cast has holes to hold the backing plate and maintain its flatness. It has tunnels below its holes which are complementary to holes on top SS chuck.

Because the 200mm by 200mm stamp will wrap directly onto the print roller, two spring plungers are installed on the surface of this adapter. Complementary holes will be drilled on the backing plate, and the backing plate will align itself with the vacuum chuck by inserting the plungers into holes. When the wafer chuck is flipped over onto the SS chuck, the plungers will contract into SS chuck. The description of spring plungers can be found in Datar[25].

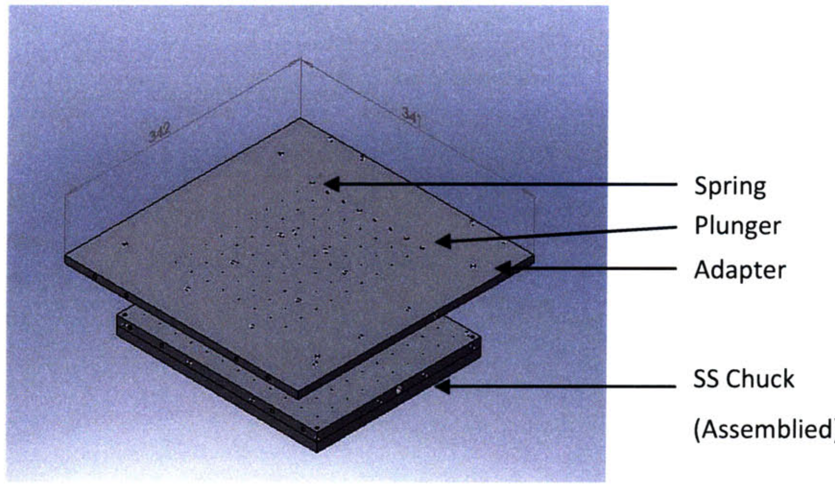


Figure 4.5 3D Model of Adapter of SS chuck for 200mm size stamp fabrication.

4.2.4 Assembly of Stamp Casting Machine

Assembly and clamping follow the method described in Chapter 3.1. The actual design includes channels for PDMS injection and air vent. All three assemblies (6", 8" and 12" wafer) use the same bars to clamp and align. For clearer view of the inside area between chucks, the wafer chucks are represented by wireframe.

Thin piece of dams are added between the wafer and backing plate to cast different shape of stamp other than circular. In the test conducted at Nano-Terra Inc. we inserted Round Teflon with square hole inside for square stamp.

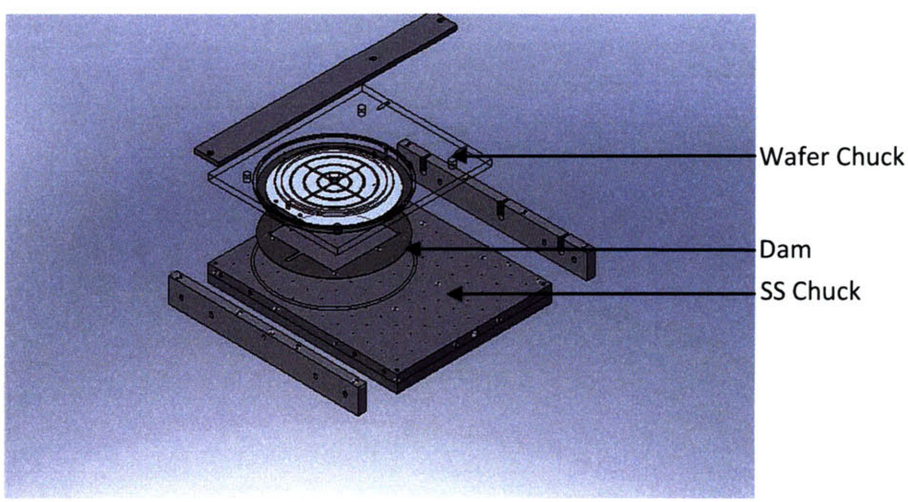


Figure 4.6 3D Model of Assembly for 6" wafer (exploded view). The wafer chuck is

represented by a wireframe for a clearer view inside the structure.

In 6” wafer assembly the SS chuck top is not entirely covered. Air may leak into vacuum if backing plate is not long enough. In actual operation tapes are used to cover these holes. The 8” wafer assembly requires backing plate big enough to cover all areas on wafer (Figure 4.7).

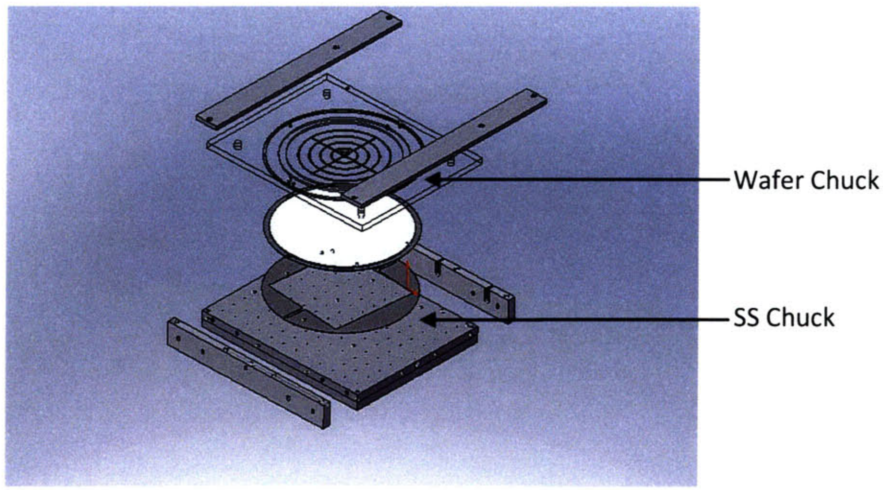


Figure 4.7 3D Model of Assembly for 8” wafer (exploded view). The wafer chuck is represented by a wireframe for a clearer view inside the structure.

Unlike the assembly for 6” and 8” wafer, 12” wafer assembly connects its clamping and sidebar directly to adapter (Figure 4.8).

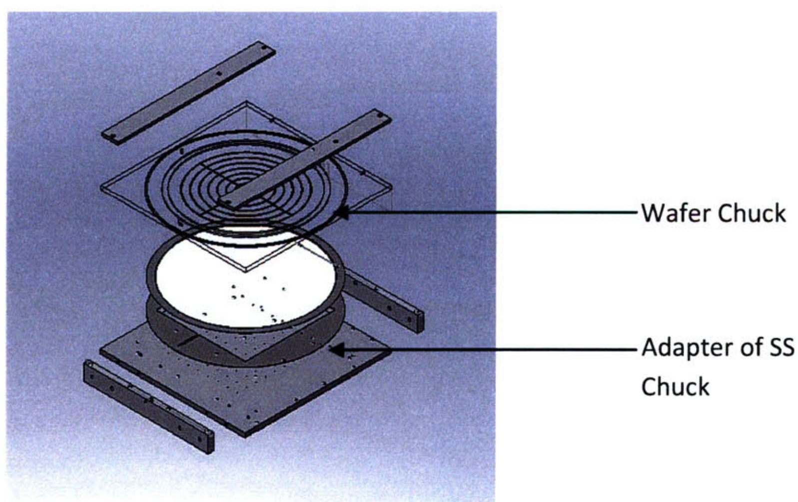


Figure 4.8 3D Model of Assembly for 12” wafer (exploded view). The wafer chuck is represented by a wireframe for a clearer view inside the structure.

4.3 Roll to Roll Machine Revisions

4.3.1 Introduction

This section is about the multi-layer printing concept design and verification with updated R2R machine. These work was done by Wenzhuo Yang and Yufei Zhu. Section 5.3 will describe the result of actual multi-layer printing conducted in Nano-Terra Inc. In Wenzhuo's thesis "Design and Manufacturing of High Precision Roll-to-Roll Multi-layer Printing Machine- Result and Experiment"[24], the actual printing process and the result are described in detail.

The roll to roll machine developed in 2008[4] proved quality printing of monolayer with a speed up to 400 inches/min. Although the result is significant, industrial application is extremely limited because most processes need multiple layers. Since printing thiol onto gold substrates is a mature technology in Nano-Terra Inc., we applied the same process for multi-layer printing in the roll to roll machine.

Several changes have been made to enable current roll to roll machine to print multilayer patterns:

1. Parts in impression roller assembly have been replaced for increased repeatability;
2. The print roller has been installed onto a flexure, allowing fine adjustment at the level of 1 micron; (see Paolo Baldesi [26] for details of the adjustment process).
3. The PLC was reprogrammed to more accurately control the stepper motors in the machine.

In addition, two microscopes were installed to measure offsets between layers.

Modifications in print roller and impression roller enable accurate contact between substrate and stamp surface. The control system has been reprogrammed to create a tension free area on the substrate during second layer printing. Detailed operation procedure and the results of test are introduced in Chapter 5.

4.3.2 Process of multi-layer printing

We redesigned the roll to roll machine with a process similar to Gravure printing: By acquiring the offset of two layers, the system sends out instructions to actuators, and actuators compensate for the misalignment. Different from gravure printing, where multiple rollers print layers on the fly, the roll to roll machine can only print one layer at a time. In this project, we print the first layer without developing the pattern, and etch the gold on the substrate whenever a preset length of second layer has been printed (Figure 4.9).

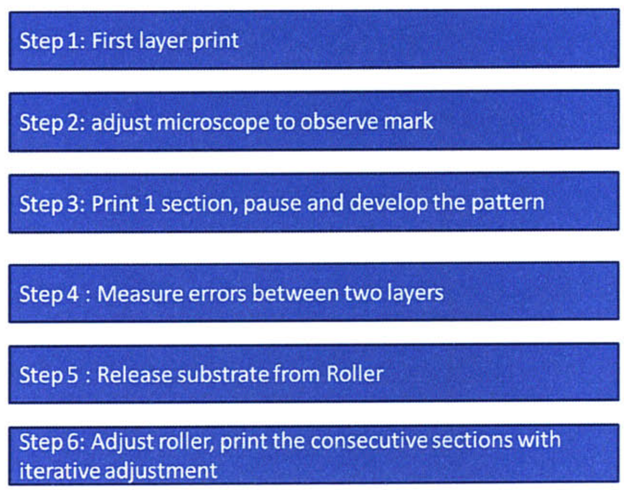


Figure 4.9 Summary of steps for multilayer printing on flexible substrate

Step 1(Figure 4.10): First layer of pattern is printed on the entire roll of substrate. The substrate will then be rewound to the initial location. The control program is the same as roll to roll machine's original program for continuous printing. To reduce distortion, the substrate will be guided along its path with minimum tension. Marks are printed in each section on substrate but invisible until being developed in step 2.

In Figure 4.10, Patterns are transferred (section1, section2 and section3) when stamp on roller contacts the substrate. Vacant areas on roller result in seam on substrate.

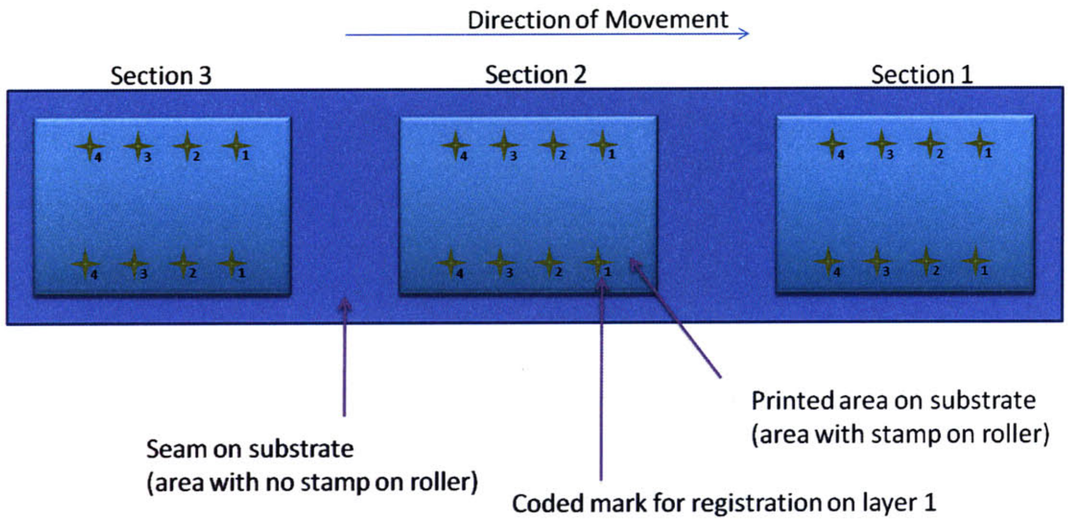


Figure 4.10 Critical pattern on surface of substrate

Step 2 (Figure 4.11): Before the substrate touches the print roller again, a small area at the edge of the front end of substrate is developed to create a visible mark. Once the microscopes are fixed to a position where clear marks can be observed, the impression roller brings down the substrate to contact print roller. When the contact is established, the collect roller which drags the substrate will be relaxed to cancel tension. Print roller rotates one full circle and print the second layer.

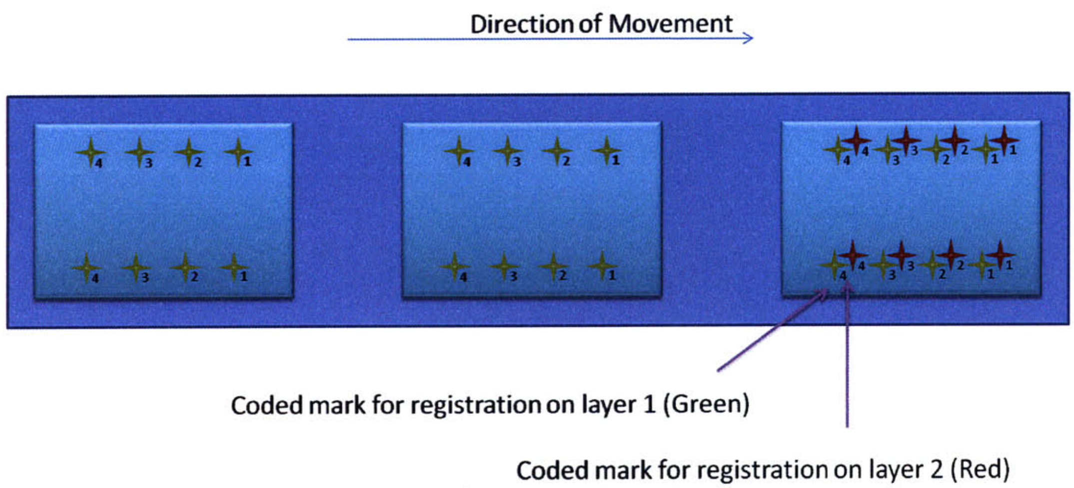


Figure 4.11 Critical pattern on surface of substrate after second layer is printed

Step 3 (Figure 4.12): Before aligning substrate for observing the pattern with microscopes, the impression roller is lift up to separate the substrate from print roller. After the separation the substrate is free for adjustment. The first section of substrate will again be developed to observe the pattern. The substrate will be wound and rewound back and forth until microscopes capture the two layers on substrate.

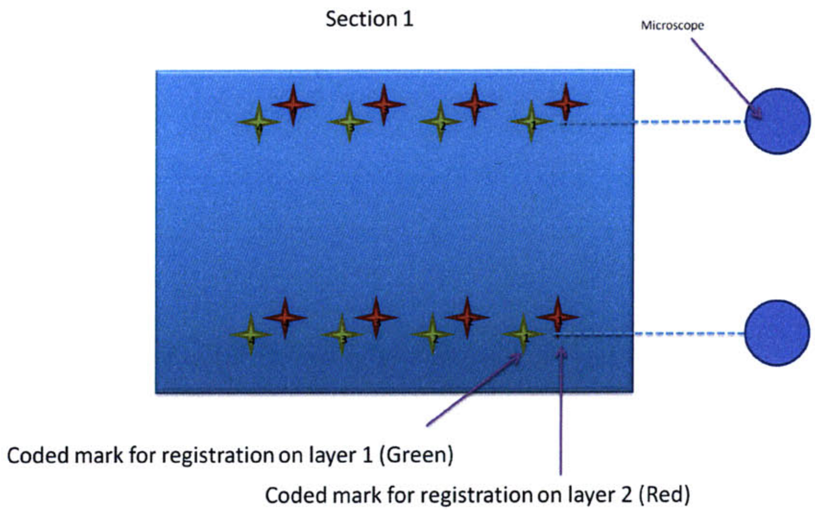


Figure 4.12 The microscopes will observe the marks when substrate is adjusted.

Step 4 (Figure 4.13): The error of two layers will be measured by microscope.

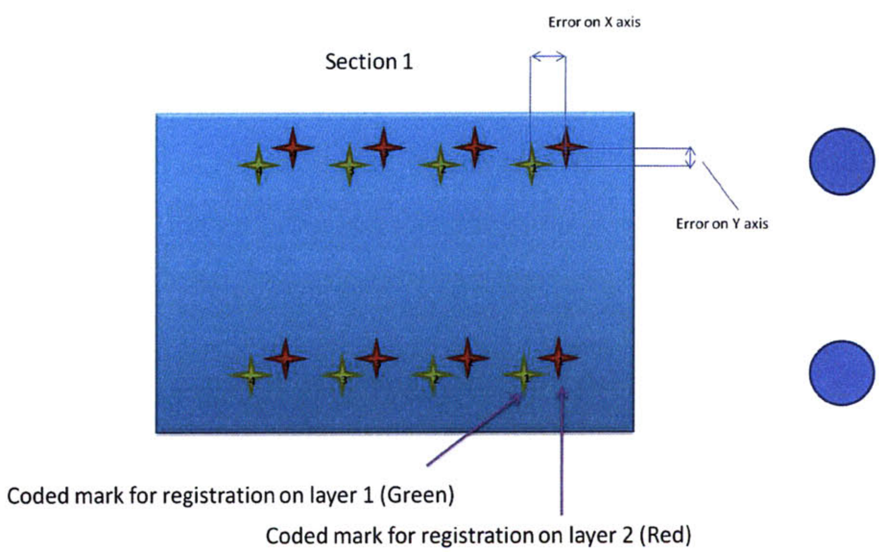


Figure 4.13 Measurement of error of layers.

Step 5, 6 (Figure 4.14): Print roller is adjusted to reduce the errors. The roller has five degrees of freedom and can be adjusted for maximum 13 microns in all lateral directions. Please refer to print roller section for detailed design. After adjustment, resume the print for certain distance and until another section is printed.

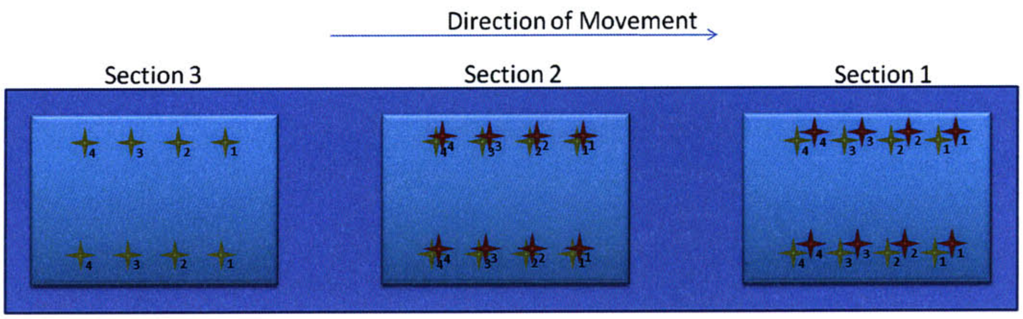


Figure 4.14 Errors are expected to be reduced every time a new section is printed.

By iterating the steps described above, a convergence of error is expected.

4.3.3 Print Roller

The revision of print roller assembly has two major parts:

1. Replace the aluminum roller by a magnetic roller with the same dimension (Figure 4.15).
2. Use a High Precision Positioning System to support the magnetic roller and adjust the position of roller in five directions.

By using a magnetic stainless steel as the backing plate, the new print roller can generate strong and uniform force when wrapping the backing plate onto the roller, increasing the repeatability of alignment of stamp and print roller. Please refer to Charudatta Datar's Thesis for detailed design process[25].

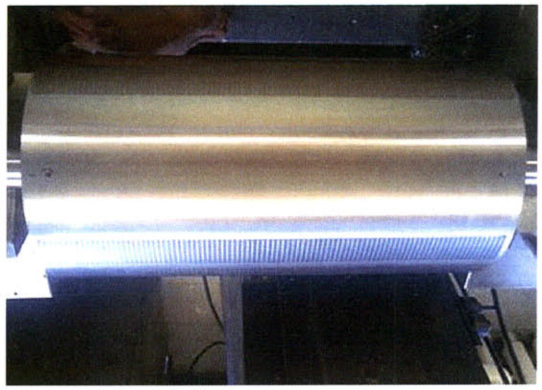


Figure 4.15 Magnetic Roller[26]

The High Precision Positioning System which supports the new print roller has five degrees of freedom (Figure 4.16) and allows fine adjustment in all five directions. Figure 4.17 shown the actual structure of this system designed by Paolo Baldesi[26].

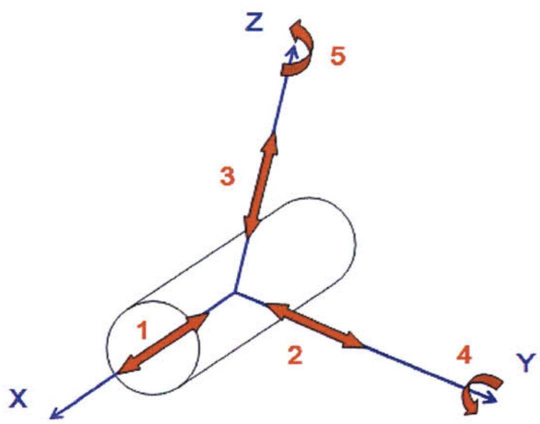


Figure 4.16 Degrees of freedom controlled by the Positioning System[26]

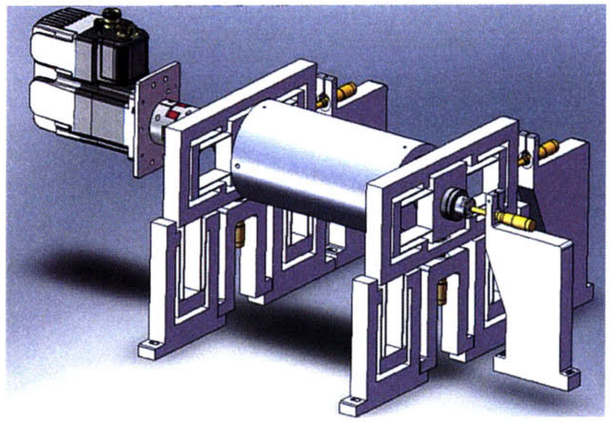
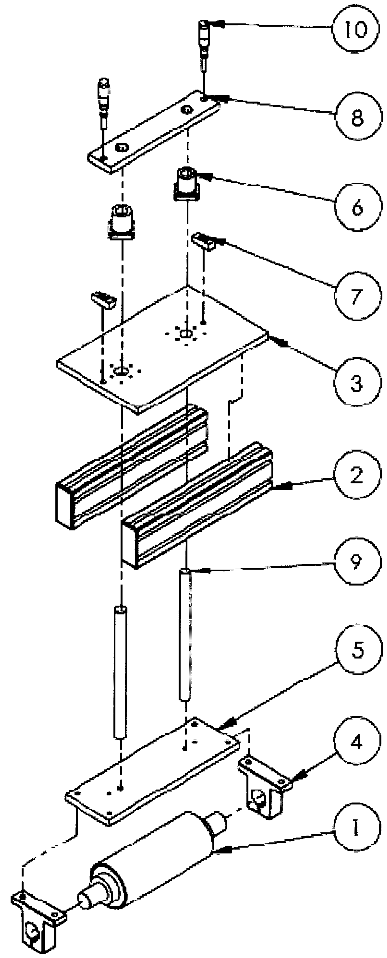


Figure 4.17 CAD model of the proposed final design of the positioning system[26]

4.3.4 Impression roller

The Impression roller assembly was modified to increase the repeatability of substrate positioning. By doing this, impression roller can return to its original location precisely, allowing print roller adjust itself with accurate reference. It is also beneficial for future applications other than self-assembly printing. These applications require better pressure control during printing.

Experiments conducted in 2008[4] indicated that when printing pressure falls in the range of 15.88kPa to 41.14kPa (or 3.5lbs to 26.8lbs as overall load), quality of printing is not affected by change of pressure [4]. Because of this, a loose design has been used in the print module of the machine (Figure 4.18).



ITEM NO.	DESCRIPTION	QTY.
1	IDLER ROLLER ASSY	1
2	8020 STANDOFF	2
3	IMPRESSION FIXED PLATE	1
4	SHAFT MOUNT	2
5	SHAFT SUPPORT PLATE	1
6	LINEAR BALL BEARING	2
7	LOAD CELL	2
8	PRESSURE PLATE	1
9	LINEAR SHAFT, .750"	2
10	MICROMETER	2

Figure 4.18 Exploded view of impression Assembly and Bill of Materials [4].

The experiments were carried out by loading impression roller onto a stationary inked printing roller with a strip of substrate in between (Figure 4.19). The developed patterns in gray represent the actual contact area between impression roller and printing roller.

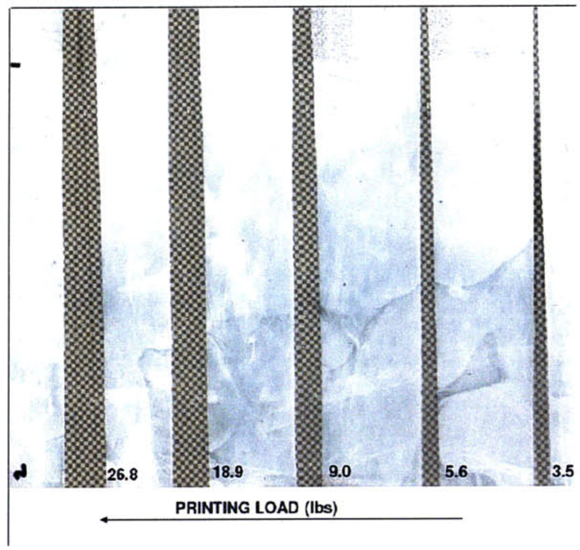


Figure 4.19 Image of different load from impression roller [4].

Because alignment is not easy to achieve, impression roller and print roller are not parallel and the contact area is tapered. With pressure under 3.5 pound (line at the left in figure 4.) the top width is 0.09 inches, and bottom width is 0.23 inches [4].

Item	Description	Qty	Manufacturer	Vendor	Part #	Error
1	MODULE PLATE, PRINT	1	NT-MIT	MD Belanger	P101	0.075mm/40cm
2	SHAFT SUPPORT PLATE	1	NT-MIT	MD Belanger	P114	0.075mm/40cm
3	IMPRESSION FIXED PLATE	1	NT-MIT	MD Belanger	P116	0.075mm/40cm
4	IDLER ROLLER ASSY	1	DFE	DFE	IR3-8-45	N/A
5	LINEAR BEARING ASSY	2	THOMSON	M-C	64825K36	N/A
6	LINEAR SHAFT, .750″	2	THOMSON	M-C	6649K61	0.002″/12″
7	SHAFT MOUNT	2		M-C	6068K27	N/A
8	8020 STAND OFF	2		8020		N/A

Table 4.1 List of parts in impression assembly [4]

To enable accurate alignment during step 5 and step 6 described in section 4.2.3, the impression roller to which substrate will comply to was improved for enhanced repeatability during its linear movement. The target repeatability is 3 micron every time the impression roller returns to the print location (adjusted by micrometer with resolution of 1 micron). The solution is to use a precision shaft and bushing in place of the plain shaft and bushing installed (Part No. 6 and No.9 in Figure 4.18). The precision shaft and bushing are shown in Figure 4.20 and Figure 4.21.

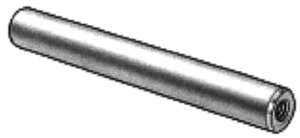


Figure 4.20 The Updated Precision Shaft

Figure 4.21 The updated Linear Ball Bearing

4.3.5 Control system

Because the substrate (PET) will distort under tension, the roll to roll machine was reprogrammed to create a tension-free area for second layer print, and tension control is not necessary at this point.

We have also increased the number of micro-steps in stepper motor [4] to 256. The motor has 200 full steps, and in order to run a full rotation 51200 pulse are needed. High speed I/O was configured from speed model to position model. Because the frequency of pulse cannot be lower than 40 Hz, loss of steps occurs. On average the error is 5 steps.

4.4 Multilayer printing machine for solid substrate

4.4.1 Introduction

Nano-Terra Inc. is also interested in a machine capable of multilayer patterns printed on solid substrate. Some projects at the company require high pressure and zero friction between substrate and roller. Synchronized movement of substrate and roller is one of the major specifications in this machine. Similar to the roll to roll machine, roller should be able to retrieve from print position and maintain alignment each time it is replaced. In this section a analysis and proposed system structure (never realized) is presented for this design the registration sensing method is the same as described above.

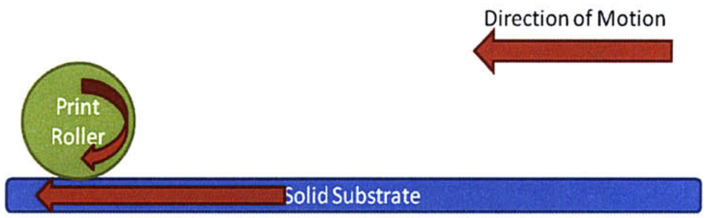


Figure 4.22 Schematic illustration of synchronized movement of substrate and roller

To realize a synchronized movement, two concepts have been proposed:

1. Use completely independent drivers for both substrate and roller,
2. Let external motion synchronize both drivers.

The former is ideal for controlling the print quality, however knowing the relationship between substrate's linear motion and roller's rotary motion very accurately is a prerequisite. Accordingly this following uses the latter approach initially.

4.4.2 Proposed System Structure

We have selected the concept of adding up different modules to build the machine . Each module has its own function and interaction between modules will be minimized. The requirement of this system is

- The system enables accurate postioning of both roller and substrate.
- Syncronized movement between roller and substrate with minimum friction at the surface of contact can be realized,
- The system has to be upgradeble for real-time feedback if higher accuracy and speed of printing is required.

The refrence axises we are using in the following design and analysis are:

- The X direction is the direction for printing, substrate will move along this direction. It is also considered as the path of printing;
- The Y direction is the direction perpendicular to path of printing;
- The Z direction is the direction perpendicular to the surface of conformal printing.

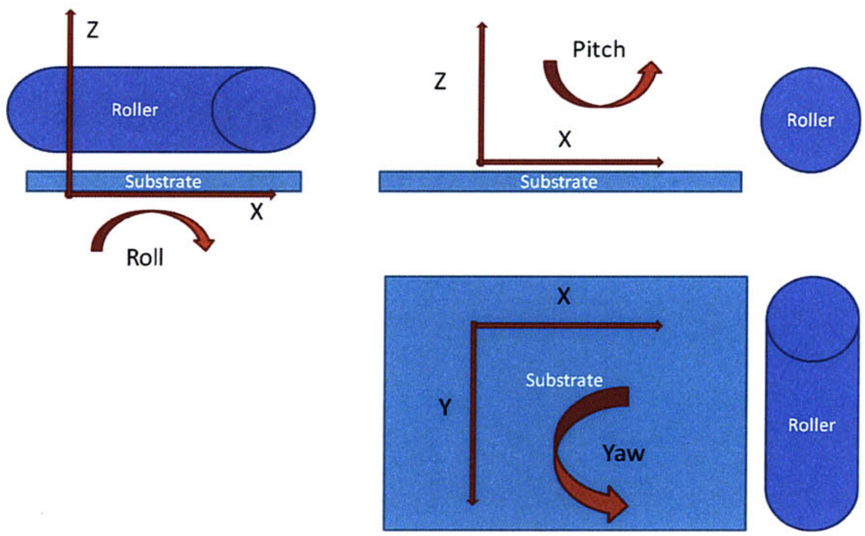


Figure 4.23 Reference axis for error analysis

Two system structure has been proposed (Figure 4.24 and Figure 4.25).

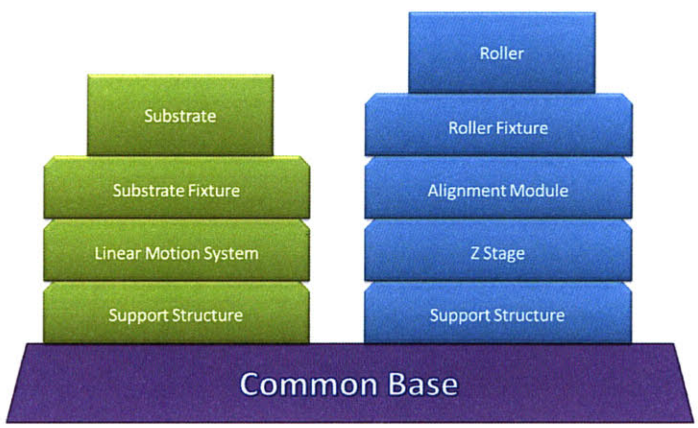


Figure 4.24 System structure I

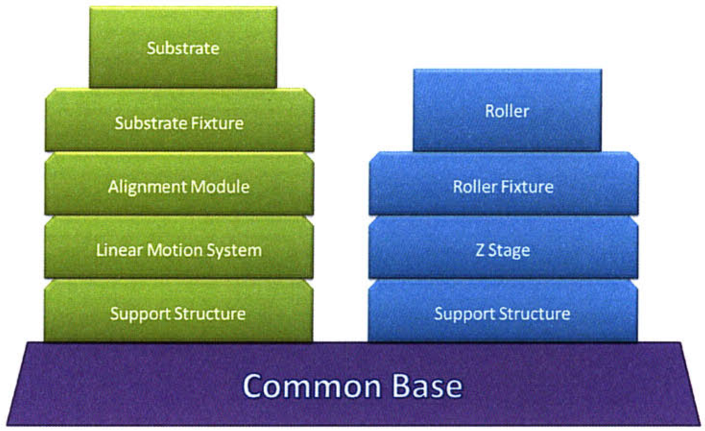


Figure 4.25 System structure II

The only difference between the two structures is the location of alignment module. In practice, parts that are frequently changed should be aligned frequently. Because the roller has to be retrieved from the printing position frequently, we were inclined to use the first structure, which allows the roller adjust itself before printing. However in real manufacturing, the substrate will be changed all the time and second structure is more applicable.

4.4.3 Function and Requirement for Main Components

Common Base:

The common base is where all the components are fixed onto a single foundation. It must be rigid enough for holding both support structures, while isolating vibration that may affect the quality of printing. An optical table is an appropriate component for this part of system.

Figure 4.26 Location of Common base. This component will convey every component of system.

Support Structure:

All actuation systems will be fixed onto the support structure. Because the height of actuation systems for both print roller and substrate may be different, the support structure will be used to level up the upper systems. The requirements of this component include:

(1) Capacity should be high enough to hold upper structure in order to maintain the position of upper structure when center of gravity has changed.
(2) No interference with other parts.
(3) Isolate vibration from other parts of the system.
(4) Firm Connection with common base/lower structure.

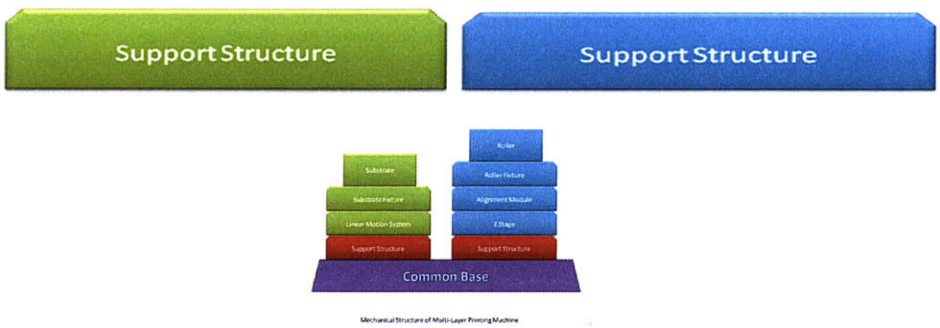


Figure 4.27 Support structure will be customized to support both systems.

Linear Motion System

The linear motion system creates the roller path and pull/pushes the substrate along the path. Controlling the position of substrate during print is one of the most critical issues in achieving a high accuracy of pattern. The requirements of this component are

(1) Load capacity is high enough to lift/support the substrate and its fixture.
(2) Position is accurate in the direction perpendicular to motion.

Figure 4.28 Linear motion system conveys the substrate and its fixture.

Substrate Fixture:

The substrate fixture connects the linear motion system and the substrate. It also serves to adjust the substrate and reduce the error described in next section.

Requirements:

(1) Rigid enough to hold the substrate and limit any motion of substrate in all direction under different printing pressure.
(2) Connection with linear motion system is stiff enough to prevent relative motion under the load and applied force.
(3) No internal deformation during printing.

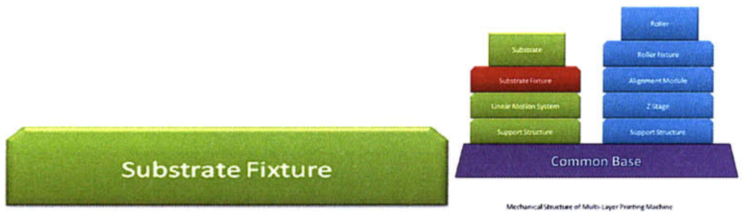


Figure 4.29 Substrate fixture will define substrate's position.

Z stage

The print roller has to be removed and reinstalled to print different layers. A Z stage is added to move the roller from print position to the position for replacement. The Z stage has to be able to support the load of upper components and firmly connect to the common base.

Figure 4.30 Z stage is used to move its upper component vertically.

Alignment module:

Alignment module for print roller is the same as the one used in revised roll to roll machine. Its requirements are:

(1) Allow adjustment in 5 directions.
(2) Enough capacity to support roller.
(3) Maintains position while printing.

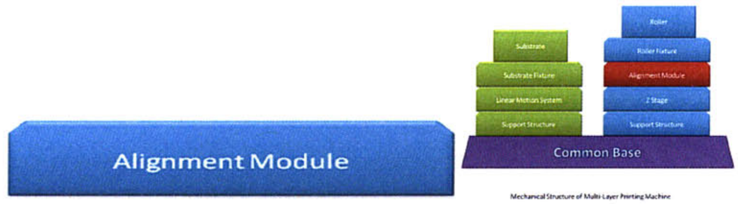


Figure 4.31 Alignment module adjusts position and angle of roller.

The Flexure designed for revised roll to roll machine (see Baldesi [26]) fulfills these requirements and can be used directly in this machine.

4.4.4 Analysis of error for machine structure I

An analysis of error was carried out to determine the detailed specifications (Material, Dimensions and process involves) of each component. An error budget was form at the end to show the result and potential improvement for higher accuracy.

We focused on analyzing the static error in the system. Static error includes installation error, resolution of the actuator (stepper, screw etc.) and resolution of microscope/detector. If the error can be feedback through microscope/detector, the static error will be solely determined by microscope/detector or actuator, whichever has a lower resolution. If a feedback loop cannot be established, the static error equals the resolution of calibrating system.

X direction:

Error in this direction will be sensed by operator through feedback system. It is build up by:

$$\delta x = \delta Resolution\ of\ stepper\ or\ \delta Resolution\ of\ microscope + \delta Bearing$$

Y direction:

Error in this direction will be compensated by alignment module. Compositions of this error are:

$$\delta y = \delta Resolution\ of\ screw\ or\ \delta Resolution\ of\ microscope + \delta Bearing$$

Both error in X and Y translational direction results in offset between layers shown in Figure 4.32.

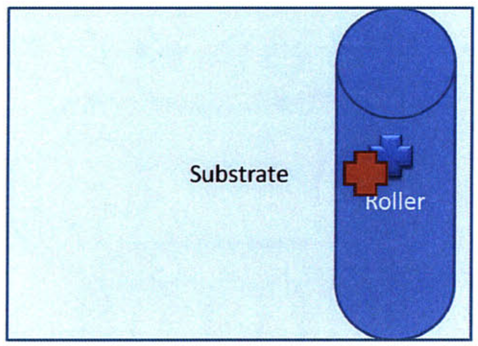


Figure 4.32 Error in translational direciton

Z direction:

The error will be compensated by adjusting the roller. Pressure sensors are expected to be installed at the both ends of the roller if pressure control is important. The error in Z translational direction will equal to the resolution of pressure sensors.

Pitch:

Error in pitch is resulted from tilt of substrate during its movement (Figure 4.33) Data from last year's project indicated that the maximum pressure for printing is 40Kpa[4]. The young's modulus of PDMS is approximately 700Kpa. Assumes thickness of PDMS is 500 micron, the maximum amount of substrate shift because of error in pitch is

$$\delta z = 500 \times \frac{40}{700} = 28\text{Micron}$$

If the shift of substrate exceeds this number, pattern will be distorted.

The error of pitch is composed of

1. Angular error of cartridge surface and its axis of motion;
2. Fixture's inherent tilt;
3. Substrate's uneven surface.

$$\boldsymbol{\delta pitch = \delta linear\ motion\ system + \delta fixture + \delta substrate}$$

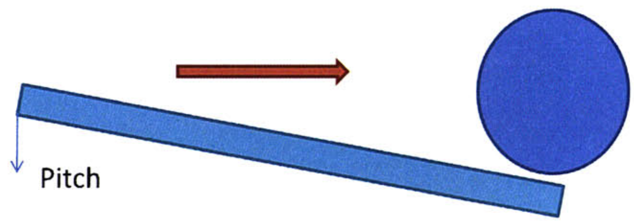


Figure 4.33 Influence of pitch during printing

The summation of errors must meet the allowance of pitch for maintaining the shape of pattern being printed.

Yaw:

Error in Yaw will affect printing quality along the axis. The offset in Y direction for patterns will be equal to this error.

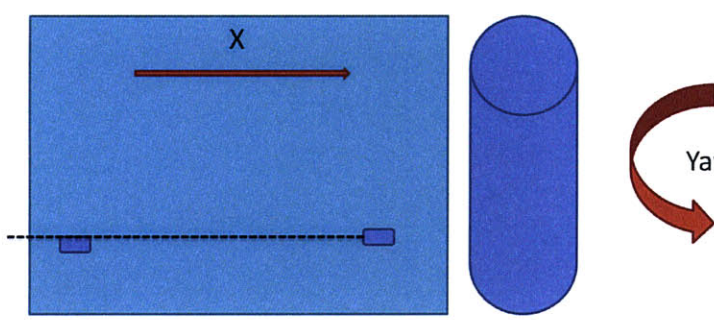


Figure 4.34 Influence of Yaw in printing.

We proposed to use one edge of glass as datum. This lateral boundary will be aligned with one surface on fixture (this fixture will be pre-calibrated), and the error of yaw equals the resolution of calibration system.

The error of yaw includes inherent error of linear motion system, the install error and relative error between substrate and mark:

$$\delta yaw = \delta linear\ motion\ system + \delta resolution\ of\ microscope + \delta substrate + \delta mark$$

Roll:

Error in roll will result in unbalanced load along the axle of roller. We expect to maintain this error within 5 micron and differences in pressure at two end of roller will be less than 7kPa.

Error Budget:

An error budget has been formed using the analysis above. Also included is suggested improvement for the machine if higher accuracy is targeted.

Axis	Source of Error	Value(μm)	Required Instrument/Process to improve
X	1 Stepper	10	Use stepper with more than 2.1E5 steps
Y	1 Screw	1	
Pitch	1 LMS	5	Use high resolution actuator
	2 Fixture	20	Use Sensor with resolution higher than 1 micron for calibrate
	3 Substrate	20	Variance of substrate thickness is less than 1 micron
Yaw	1 LMS	5	Use higher resolution actuator to reduce increment of each step
	2 Microscope	20	Microscope with better resolution
	3 Substrate	20	Substrate with flatness of 1 micron or less
	4 mark	5	Repeatablity of mark is less than 1 micron

Table 4.2 Error budget and suggested instrument for reducing the error.

Notice errors are mainly associated with the substrate, fixture and microscope. This is due to the limitation of the vendor for machining and limited budgets_available from the revision of roll to roll machine.

Due to the limited time, this design was not manufactured for testing.

5. Results

This chapter introduces the experiment and measurement carried out in this project. Comparison between updated system and previous system is covered. Results include:

1. The quality of critical components processed by vendor for stamp casting machine;
2. Distortion of the single layer pattern printed by upgraded Roll to Roll machine;
3. Accuracy of alignment of the multi-layer printing.

For more detail regarding the means of measurement, description of equipment involved as well as data processing, please refer to Wenzhuo Young's thesis[24].

5.1 Flat Stamp Fabrication

5.1.1 Stainless steel chuck

In the new stamp casting machine, the flatness of stainless steel chuck (SS chuck) directly affects the quality of stamp being cast. This is because the backing plate sticks onto the SS chuck with vacuum, and the surface of backing plate will has the same topography as the surface of SS chuck. All other components (wafer, dam etc.) are standard component and are relatively flat compared to the SS chuck.

We used an automated confocal microscope to scan the height of SS chuck received from the vendor. With two sets of 10x10 points, the topographic charts of two vacuum chucks are plotted and shown in Figure 5.1 and Figure 5.2:

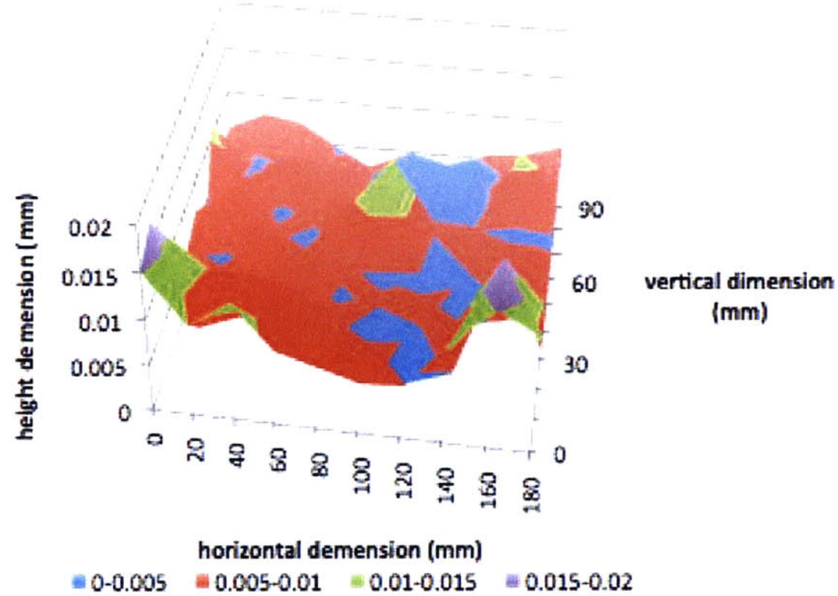


Figure 5.1 Topographic Mapping of SS Chuck

The range of the flatness is 22μm for this year's vacuum chuck. Also the standard deviation of the flatness for the new vacuum chuck is 3.6μm.

5.1.2 Measurement of Flatness of the Stamp Surface

To make a comparison between quality of stamp casted with the new machine and the old ones (Figure 2.6), we cast stamps with both machine and measured with the automated confocal microscope. Both stamps are adhered to the stainless steel sheet, and the SS sheet is held by vacuum chuck.

After a scan of 10x10 points; the data has to be adjusted to eliminating the slope impact of the measurement platform. The topographic mappings of two stamps are plotted and shown in Figure 5.2 and Figure 5.3

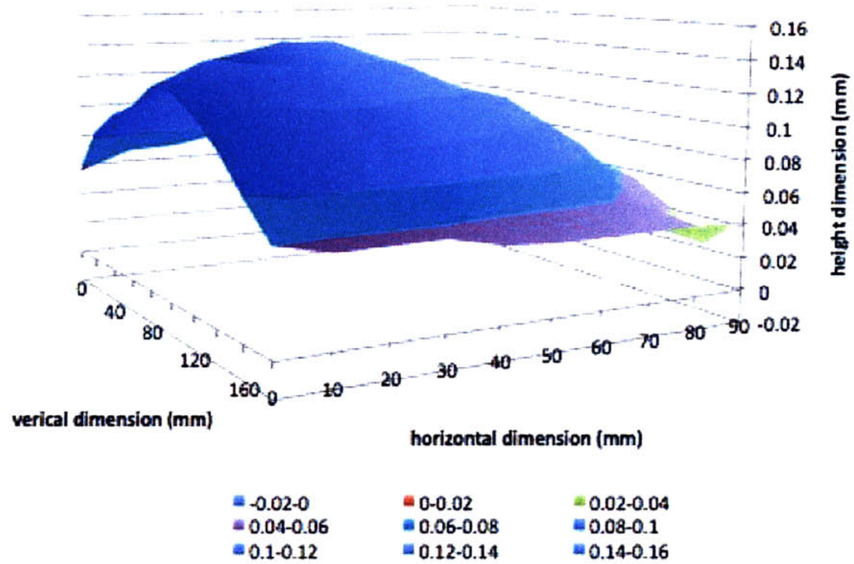


Figure 5.2 Topographic mapping of the stamp fabricated using previous stamp casting machine

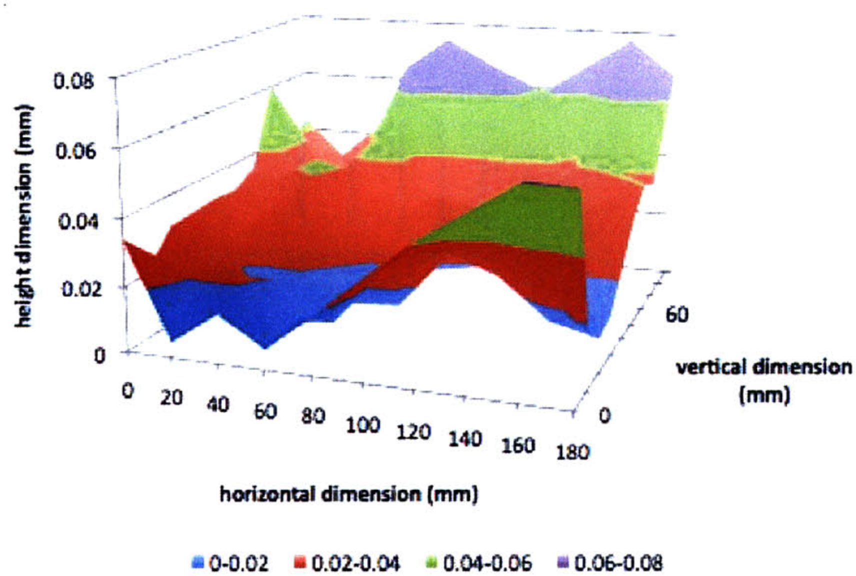


Figure 5.3 Topographic Mapping of The Stamp Fabricated Using the new stamp casting machine.

It is observed that the curvature pattern of the stamp surface aligns with that of the vacuum chuck, which proves that the surface of the vacuum chuck does impact that of the stamp. After eliminating the impact of the vacuum chuck by deducting the data of vacuum chuck from the stamp surface measurement, the previous stamp fabrication process generate 125μm as the range of stamp's flatness and the updated process generate the range of 67μm. Although the number about the variance of the stamp is not 100% accurate because of the stainless steel sheet property and deformation of the stainless steel sheet caused by the suction of vacuum chuck, a big improvement of the flatness of the stamp could still be seen.

5.1.3 Measurement of the Thickness of the Stamp

Uniformity of thickness of the stamp is another quality we were interested in. In order to obtain the thickness of stamp, we first measure the absolute height of stamp sitting on the SS chuck, then remove the stamp and measure the absolute height of SS chuck. The difference of average height with/without stamp equals the thickness of the stamp.

After taking 40 sample points on the surface of the stamp and 10 sample points on the surface of the platform, we first adjusted the slope impact from the measurement platform and then calculated the thickness of the stamp by taking the height difference of the stamp and the platform. Using previous fabrication method, the average of the thickness is 875μm with 27μm standard deviation. The updated method has the average thickness of 1194μm with standard deviation of 9μm.

Although the thickness of new stamp is bigger than the stamp cast with the old machine, we can easily adjust its height by acquiring a thinner Teflon dam.

5.2 Single Layer Printing with Updated R2R Machine

5.2.1 Repeatability of the Parallelism of the Impression Roller

The impression roller assembly was improved for higher repeatability for substrate positioning. To test the repeatability of updated system, the modified impression roller is lifted up then put down. Two dial indicators are installed below the impression roller and 20 samples are collected.

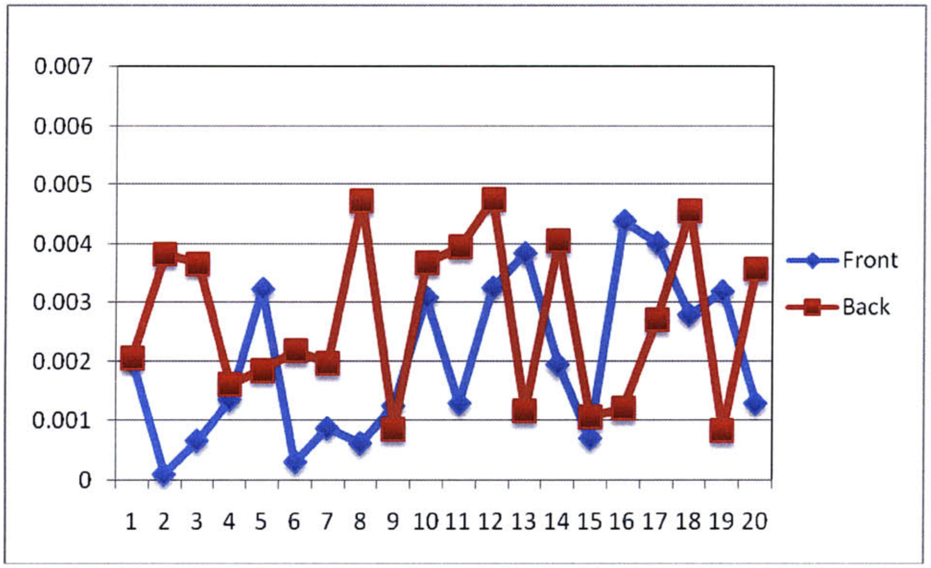


Figure 5.4 Test Result of the Repeatability of Parallelism for Updated Impression Roller System

The result showed that the displacement varied within 5μm and the test points appear to be normally distributed. During actually adjustment in multi-layer printing process where a micrometer head is used for actuating the impression roller, the average displacement and the Standard deviations at both ends are all less than 1μm.

5.3 Multi-layer Printing with Updated R2R System

Because of time limit, we demonstrated multi-layer printing with the updated Roll to Roll system with simplified process (see Yang[24]). We used the same stamp to print two exactly same patterns onto the substrate, and then develop to measure the misalignment. Ideally the pattern should overlap, and the displacement between two layer can be measured easily (Figure 5.5)

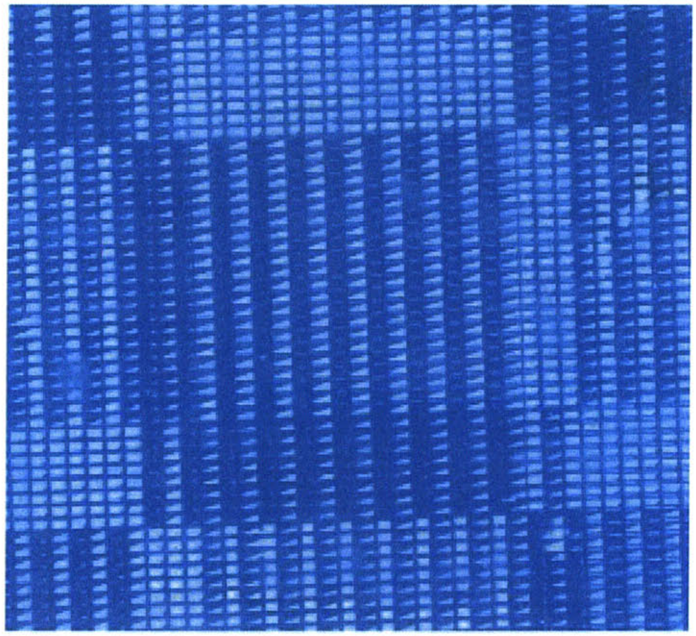


Figure 5.5 Multi-Layer Printing Result (central of 200mm X 200mm printed area)

We measured three points at the corner of printed area (Figure 5.6). Results are:

- The lower right corner showed 1017μm displacement along the printing direction and 113μm displacement across the printing direction.
- The top right corner had the displacement of 1582μm along the printing direction and 162μm across the printing direction.
- The lower right corner had displacement of 2962μm along the printing direction and 3149μm across printing direction.
- The top left corner was out of the substrate and can't be measured.

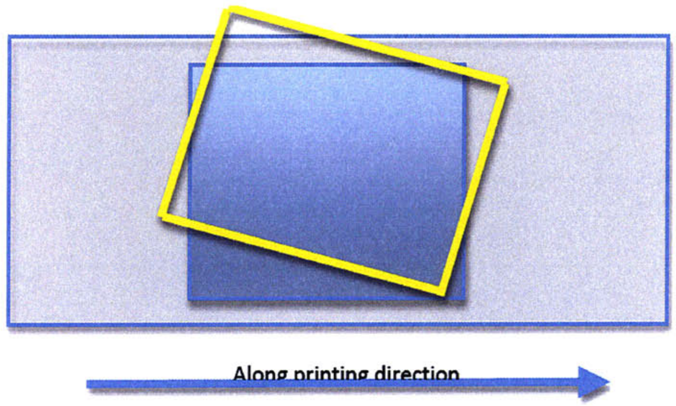


Figure 5.6 Relative positions of two layers[24]

The maximum displacement of two layers printed is around 3mm. We have done several trials and better results were observed. The demonstration indicates the process is feasible with the upgraded Roll to Roll machine.

In order to achieve higher accuracy in multi-layer printing, we recommend acquiring new components for current Roll to Roll machine. These components include:

- Accurate position stepper motor;
- Microscopes with higher resolution;
- Precision machined rollers for substrate control.

Next chapter will explain the necessity of these components.

6. Summary and Future Work

We have updated the Roll to Roll machine built in 2008[4] for multi-layer printing capacity. These improvements include:

1, Manufactured a stamp casting machine for better stamp quality;

2, Replaced the print roller assembly with magnetic roller and Flexure design for fine adjustment;

3, Introduced an innovative wrapping process for repeatedly wrapping the backing plate onto roller;

4, Designed multilayer printing process and achieved preliminary results.

Because of time limitations, some results were not as good as we expected. For example, the flatness of stamp is limited to the surface finish of parts in stamp casting machine. Higher uniformity of the stamp is achievable if critical component of the device can be process with better tools.

Also a better detection device can be brought in to measure the error in multilayer printing. The detection method needs to be analyzed and redesigned so that continuous feedback without manual signal processing is possible.

In addition, we recommend several changes could be made for the purpose of increasing the accuracy of multi-layer printing:

1, The current stepper motors are not suitable for precision positioning. Better motors or continuously variable closed-loop motors are beneficial to accurate printing.

2, Web handling is critical in achieving registration. A restricted and controlled path for the substrate can be created by redesigning some of the web components in the present roll to roll machine.

3, We disabled the tension control components in the machine to create a tension-free zone on the substrate during printing. However, tension control should be resumed if continuous printing is desired for multilayer printing.

7. Reference

[1] Xia, Y. and Whitesides, G. M., 1998, “Soft Lithography”, Annual Review Mater. Sci. 1998. 28:153–84

[2] Nano Terra Inc, <http://www.nanoterra.com/i/self_assembly_diagram_1.gif>. Accessed 8/1/2008.

[3] Michel, B. et al., 2000, “Printing Meets Lithography: Soft Approaches to High resolution Patterning”, IBM Journal of Research and Development, 45(5)

[4] Stagnaro, A.; "Design and Development of a Roll-to-Roll Machine for Continuous High-Speed Micro-contact Printing"; Massachusetts Institute of Technology, 2008

[5]. Z.-Q. Gong and K. Komvopoulos. Effect of surface patterning on contact deformation of elastic-plastic layered media. Journal of Tribology, 125(1):16-24, 2003.

[6] K. L. Johnson. Contact Mechanics. Cambridge University Press, 1987.

[7] J. N. Israelachvili. Intermolecular and surface forces. Academic Press, 2003.

[8] K. L. Johnson, K. Kendall, and A. D. Roberts. Surface energy and the contact of elastic solids. Proceedings of the Royal Society of London Series A, Mathematical and Physical Sciences, 324(1558):301-313, 1971.

[9] M. Forster, W. Zhang, A. J. Crosby, and C.M. Stafford. A multilens measurement platform for high-throughput adhesion measurements. Measurement Science and Technology, 16(1):81-89, 2005.

[10] M. K. Chaudhury and G. M. Whitesides. Direct measurement of interfacial interactions between semispherical lenses and flat sheets of poly(dimethylsiloxane) and their chemical derivatives. Langmuir 7(5):1013-1025, 1991.

[11] A. A. Griffith. The phenomena of rupture and flow in solids. Philosophical Transactions of the Royal Society of London. Series A, Containing Paper of a Mathematical or Physical Character, 221:163-198, 1921.

[12] D. Maugis and M Barquins. Fracture mechanics and the adherence of viscoelastic bodies. Journal of Physics D: Applied Physics, 11(14):1989-2023, 1978.

[13] Brian Cotterell, Gordon Williams, John Hutchinson, and Michael Thouless. Announcements of a round robin on the analysis of the peel test. International Journal of Fracture, 114(3):9-13, 2002.

[14] Laser Triangulation Sensors, <Http:// www.sensorland.com>, Accessed on 08/1/2009

[15] Interferometry, <Http://www.wikipedia.com> accessed on 08/1/2009

[16] Alexander H. Slocum, Precision Machine Design, Michigan: Society of Manufacturing Engineers Dearborn, 1992

[17] MTI instrument Inc. <Http://www.mtiinstruments.com/>, Optical Fiber, accessed on 08/2009

[18] Giallorenzi et al., Optical Fiber Sensor Technology, IEEE J. Auantum Electron., Vol. QE-18, No.4 1982,pp.

[19] Pawley JB (editor) (2006). Handbook of Biological Confocal Microscopy (3rd ed.). Berlin: Springer.

[20] Khanna,K; "Analysis of the Capabilities of Continuous High-Speed Microcontact Printing"; Massachusetts Institute of Technology, 2008

[21] Shen, Shawn. "Design and Analysis of High-speed Continuous Micro-Contact Printing". Massachusetts Institute of Technology. August 19, 2008.

[22] Sriram Krishnan, "On the Manufacture of Very Thin Elastomeric Films by Spin-Coating", Massachusetts Institute of Technology. September 2007

[23] Con-Focal Microscopy, <Http://www.wikipedia.com>, accessed on 08/1/2009

[24] Yang, Wenzhuo. "Design and Manufacturing of High Precision Roll-to-Roll Multi-layer Printing Machine- Mesurement and Experiment". Massachusetts Institute of Technology. August 18, 2009.

[25] Charudatta Datar, "Design and Development of High Precision Elastomeric-Stamp Wrapping System for Roll-to-Roll Multi-Layer Microcontact Printing", Massachusetts Institute of Technology. August 18, 2009.

[26] Paolo Baldesi, "Design and Manufacturing of High Precision Five Axis Positioning system for Roll-to-Roll Micron Contact Printing". Massachusetts Institute of Technology. August 18, 2009.