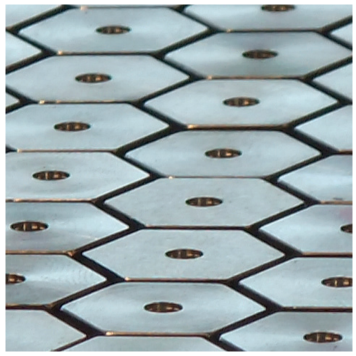
FLOATING ON A FLOWERBED

By applying a thin pressurised air film beneath a substrate, it can be levitated as well as transported and precisely positioned in all planar degrees of freedom. This avoids mechanical contact and reduces risk of damage and contamination of sensitive surfaces. Two fundamental ways of realising this combination of functions have been invented and built. High-precision positioning accuracy in the nm range and multiple-g accelerations have already been achieved in the lab. Industrial implementation is expected in the near future by a dedicated start-up.



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Introduction

In high-tech industry thin, fragile, cost-intensive products, such as silicon wafers and solar cells or glass sheets (flat-panel displays), are routinely handled and used. These substrates are susceptible to contamination, damage or even breakage as a result of any mechanical contact. Currently, special product carriers and transport systems are used for the transport of these substrates in and between the many stages that these products undergo during their manufacturing. In these existing systems mechanical contact is inevitable.

It is a strategic goal of the high-tech industry to introduce zero-contact handling and transport systems. In other words, from the introduction of the substrate at the start of the production line to the release of the product at the end of the line, there should be no (avoidable) mechanical contact between substrate and production line.

Note that existing systems that are sometimes referred to as 'contactless' are in fact only carrying the substrate without contact, but in order to transport or position the substrate accurately and fast, most of these systems still rely on mechanical contact.

Other contactless systems, such as Bernoulli grippers, which apply a levitation technique based on the Bernoulli principle, cannot freely move the object in all planar degrees of freedom (DoFs). They merely float the object to reduce contact, and rely on edge effects to maintain a centred position of the substrate on the gripper. Other systems exist that use magnetic and electric levitation, and are able to produce in-plane forces. These are promising concepts, where high precision is possible. However, they rely on specific magnetic and electric properties of the material. In air-based levitation the material itself plays a lesser role.

The concepts presented in this article are able to handle various substrates: Si-wafers, solar panel surfaces, flat-panel displays and glass, but also foil.

Operating principle

The concept is based on air-bearing technology, i.e. two surfaces with a thin film of pressurised air in between that separates both surfaces. Note that although in this article air is used as the acting medium, it is in fact possible to realise the same functionality using any gas, and with some consideration and design modifications liquid media can be used as well.

The gas-bearing concept is in itself promising in precision design, because it avoids many traditional engineering issues, such as friction, wear, backlash and lubricants. Although the concept is well-known, used mainly because of its extremely low, viscous friction, it is possible to increase this viscous traction to a level where it can be effectively used in an actuator.

A schematic example of the concept is shown in Figure 1. The actuation surface is divided into an array of regular

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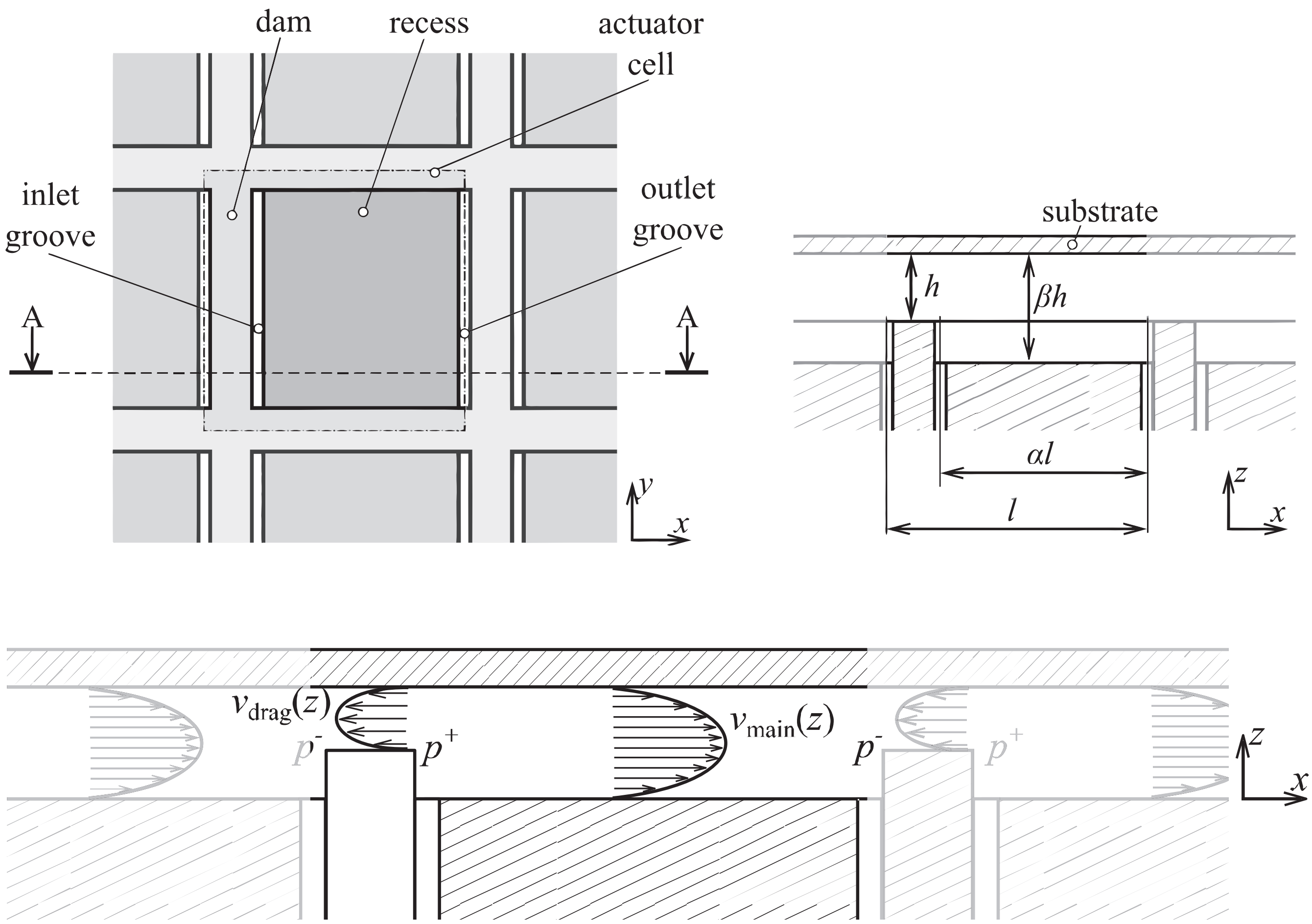

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1 *Basic principle of the contactless actuator, with the larger flow to the right creating a net viscous force on the substrate above.*

surface sections where each section consists of a pocket surrounded by dams. A typical actuator section has an in-plane length of 10 mm. The optimal pocket depth is related to the intended fly height of the substrate; for a typical fly height of 10 µm a pocket depth of 40 µm is advised. Each pocket has at least one high-pressure inlet and at least one low-pressure (sub-ambient or vacuum) outlet.

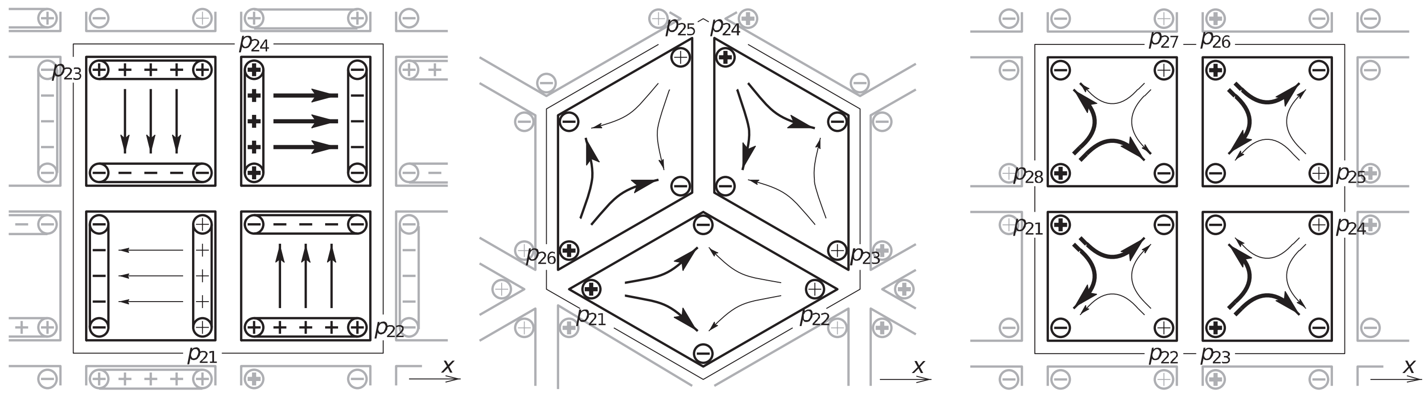
The pressure distribution under the substrate is determined by the geometry in combination with the inlet and outlet pressures. The average pressure under the substrate balances the distributed weight of the substrate that is being carried. Note that due to this combination of high-pressure inlet and vacuum outlet (push-pull concept) it is straightforwardly possible to flip the vertical orientation of the system and carry a substrate without contact hanging beneath a transport system.

The pressure difference creates a flow through the pocket from inlet to outlet, and a smaller flow across the dam that separates the pockets. Both flows are indicated in Figure 1. Due to the viscous shear of the flow a traction force on the substrate is created.

There are two variables that influence this traction, which can therefore be used to control the force on the substrate. The first variable is the pressure. By increasing the pressure difference between inlet and outlet both the flows as well as the force acting on the substrate increase. This allows the creation of a certain system with a fixed geometry, and by controlling the pressure the substrate can be positioned. Positioning systems operating on this principle are denoted to be of Gen-I (generation 1).

The second variable is the geometry. By changing the depth of the pockets, the flow distribution and the effective surface area for the pressure difference to act on will change, resulting in a change in traction imparted on the substrate. Systems operating on this principle are denoted to be of Gen-II.

Research on Gen-I was started in 2007 [1], followed by research on Gen-II in 2011 [2]. Both concepts are viable and comparable in performance, and research continues into both concepts. The combination of both concepts in one system is promising as well (Gen-III) and is another subject of study. Gen-III is not further described in this article.



(a) (b) (c)

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Gen-I: pressure variation

A big advantage of the pressure variation concept over traditional positioning stages is the elimination of the moving mass within the actuator. The substrate itself can be considered to be a monolithic moving mass, with zero in-plane stiffness and a small amount of viscous damping.

The performance of the system is defined by a number of parameters: the achievable actuation force, the deformation of the substrate due to the spatial pressure variation in the actuator and the total required volume flow of air. These main criteria were used to evaluate several designs.

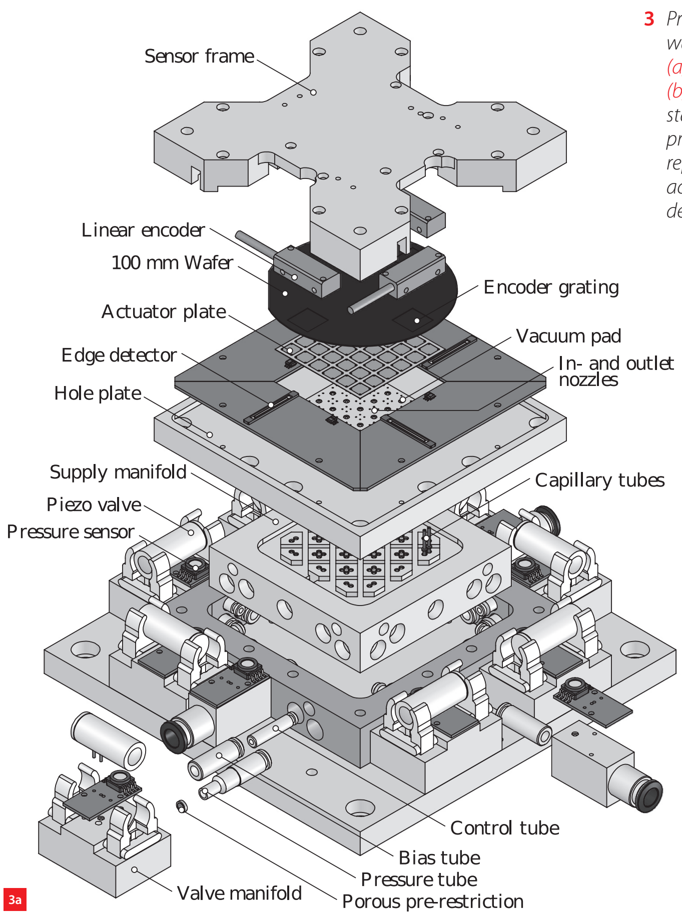
Three designs are shown in Figure 2. In each of the designs, one actuator cell can produce a force in the two translational DoFs and a torque. Design (a) has four pressure inlets per cell, design (b) has six and design (c) eight. In design (a), a translational force also produces a so-called parasitic torque, tilting the substrate relative to the actuator. This is due to the lateral movement of the resulting force carrying the substrate. In the last design, (c), this is greatly reduced.

Finite-element models (FEM) have been used to analyse the performance parameters. The design with eight pressure inlets was shown to provide the best trade-off between actuation force, parasitic pitching torques, substrate deformation and practical implementation.

A laboratory demonstrator was developed to study the Gen-I concept using the 8-pressure-inlets layout. An exploded view of the entire system, including a sensor frame for measuring the position of the wafer using linear encoders, is shown in Figure 3.

2 Three designs (see text for explanation), all capable of producing two translations and one rotation. High-pressure inlets are denoted with (+) and low-pressure outlets with (–), while fat arrows indicate the highest airflows. In these cases they create a net force to the right. Each complete system comprises arrays of these actuator cells.

3 Pressure variation waferstage [1].
(a) Exploded view.
(b) Top view of the stage with the high-precision linear encoder replaced by a less accurate, low-cost edge-detection system.



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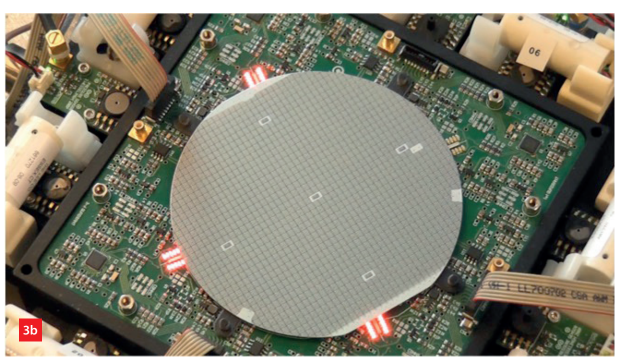

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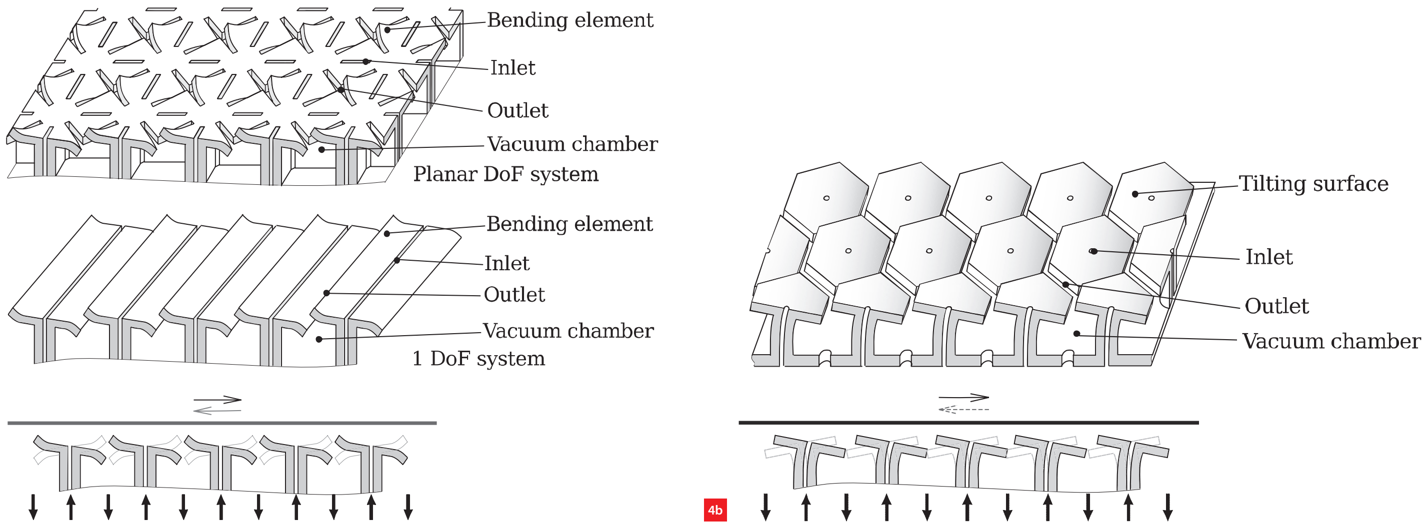


4 *Two actuator concepts.*
(a) Surface with bending sections.
(b) Surface with tilting sections.

In this demonstrator a wafer was placed on top of the manufactured actuator. With a pressure controller a steady fly height of 15 μm was achieved. For a video demonstration of this system see [3] and [4].
Lower fly heights are desirable because they come with an increase of the pressure difference in each pocket, and hence of the actuation force. Also the required airflow is substantially reduced. On the other hand, the risk of contact between plate and wafer increases.

With PID control tools and a positioning bandwidth of 50 Hz, servo errors below 100 nm were achieved, down to 6 nm (1 σ) with active vibration isolation. An acceleration of 600 mm/s^2 was achieved, limited by the maximum actuation force. By improving manufacturing tolerances, a lower fly height and therefore a higher force and acceleration can be reached.

Smaller actuators provide better performance on nearly all criteria. Therefore, the pocket size is only limited by manufacturability. Another intrinsic limitation is the delay in the pressure lines. From the pressure controller to the surface of the substrate, the change in pressure is not instantaneous, thus causing a delay that limits the bandwidth of the system. A solution to this could be pressure control right at the surface. The next concept puts this into practice.

Gen-II: deformable surface

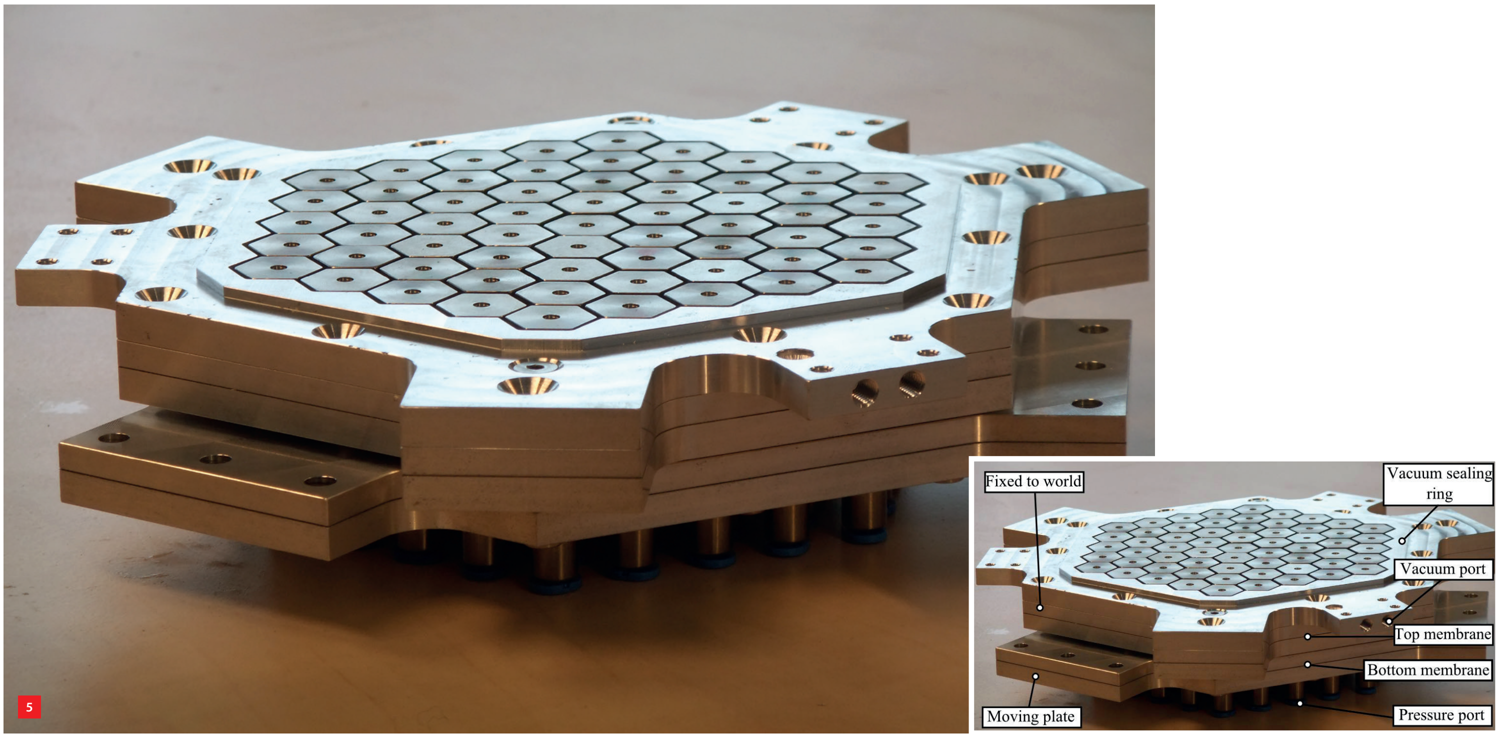
Control of the geometry of the actuator results in a direct control of the shear force generated by the flow, and does not suffer from a delay between controlling action and result. This is in contrast with the Gen-I concept where the unavoidable distance between the controlled pressure valve and the actuator surface results in a control delay, possibly limiting the overall performance of the system.

Two schematic concepts to control the surface geometry are shown in Figure 4. Surface sections may be deformed by bending piezo actuators or similar actuators, or surface sections may be tilted by deforming the carrying structure. Both concepts were found to be similar in performance, and in the first demonstrator the tilting surface concept was selected for testing. This is a variation of the concept in Figure 4b, using rigid stems: the rotation of the flowers is achieved by a translation of the bottom of the stem relative to the top of the stem [2].

The tilting surface was found to be similar in performance and a basic mechanical solution was developed to enable and synchronise the tilting of the surface sections. It turns out that the shape of the surface has very little influence on the performance with respect to the generated traction. Therefore, the shape of the final actuator was chosen such that the flow from the actuator is minimal.

Figure 4b shows the design. It consists of arrays of hexagonal surfaces, with a high-pressure inlet in the centre and a low-pressure outlet in between the surfaces. It provokes images of fields of sunflowers, all tilting their heads in unison towards the sun. Therefore, the product was nicknamed 'The FlowerBed'. The current version of the stage is shown in Figure 5.

The flowers need to tilt in unison in the required direction. Instead of actuating each flower individually, a basic mechanical solution was developed to enable and synchronise the tilting of the surface sections. Each flower has a stem connected on one side to the high-pressure inlet



5 *The FlowerBed [2].*

and on the other side to the flower head. This stem is then connected to two thin and bendable plates. One of the plates is rigidly connected to the frame, while the other is actuated in its planar DoFs. By moving this plate, all flowers tilt in unison, and direct the actuation force.

The traction control is now located right at the surface, and the time it takes from the tilting of the flowers to the variation of the traction is negligible. However, the advantage of the variable-pressure design, i.e. the lack of a moving mass, is lost because of the plate carrying the moving membrane. Therefore, the limitation of the system will in general be the actuator providing the force to move the internal mass of the system. Using capable actuators, with high speed and high force, a very high bandwidth can be achieved, dependent on the actuator characteristics. For a video demonstration of this concept, see [5].

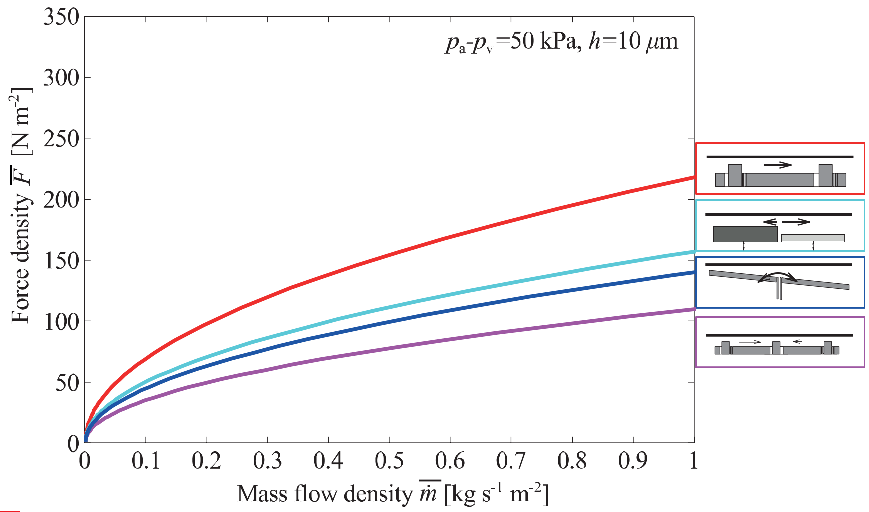
Comparison and discussion

The variable-pressure design has proven its accuracy, while the speed may leave room for improvement. The limiting delay in the pressure lines is fully omitted in the deformable-surface design, but replaced with a mechanism with inertia and stiffness.

Figure 6 shows the theoretically obtainable shear force density for a given mass flow density, compared for four concepts. It can be proven that for the assumptions inherent in thin-film theory, it is theoretically impossible to reach a higher traction value for a given mass flow density than that indicated by the red curve in Figure 6. However, note that for a traction of something like 100 N/m^2, a standard wafer with a typical mass of less than 2 kg/m^2 can be accelerated with more than 50 m/s^2. In the lab, accelerations of well over 10 m/s^2 were realised, allowing the system to move a wafer without mechanical contact along a vertical surface, working against gravity.
The best curve is related to the variable-pressure single-DoF concept (red). When the design is modified to achieve multiple DoFs (magenta), the performance drops below the deformable-surface curves (blue, light-blue). This shows that for one-directional actuation systems the variable-pressure concept would be the better choice, while for bi-directional actuation systems the deformable surface would be better.

From Figure 6 it can also be observed that the required airflow to obtain these high accelerations is huge, much higher than standard available. The use of a circulation system between vacuum outlet and supply inlet alleviates part of this disadvantage. Figure 6 is valid for a nominal fly height of 10 μm; for a smaller fly height the required mass flow density is substantially reduced. However, reliably reducing the fly height is a manufacturing challenge.

In all concepts the performance is limited by manufacturability. Tolerances, flatness, waviness and roughness determine the achievable fly height and therefore



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6 *The force per substrate area plotted against the amount of gas flow per substrate area [2], for a comparison of four fundamental concepts – in the legend on the right, from the top down:*
- Unidirectional pressure control
- Variable height
- Tilting surface
- Bidirectional pressure control.

the achievable actuation force for a certain volume flow. The current design of the FlowerBed surface consists of many separate parts, which introduces an extra challenge regarding the exact surface characteristics, compared to the advantageous monolithic surface of the variable-pressure concept.

Future development and conclusions

Two designs have been presented with comparable basic working principles but different characteristics. The variable-pressure concept can both carry and transport the substrate and achieve accurate positioning. The FlowerBed design will, in theory, improve the bandwidth and force characteristics. Since the FlowerBed is still in the experimental phase, some details of the achieved advantage are not yet available.
The limitation of the variable-pressure concept, the delay in the pneumatic lines, may be overcome by placing the control as close to the surface as possible. To achieve this, the complicated manifold should be replaced with small proportional controllable valves, just before the outlets.

Since this concept is most efficient in one DoF, transport is a logical application. In this case the valve control is extended such that only the actuator cells near the substrate are activated, while the other cells are dormant to reduce the total gas flow. In this concept cells can either fulfil bearing and motor function simultaneously, as previously discussed, or they can be divided into function-specific cells. Having separate motor and bearing cells reduces complexity and each function can be controlled separately.

Exploration of the limits of manufacturability will continue, to achieve smaller actuator cells with smaller tolerances in order to lower the fly height, increase the actuation force and reduce the pressure difference and substrate deformation.

Furthermore, the FlowerBed is still being improved mechanically. Difficulties arise in the high-precision alignment of each separate flower surface compared to the others, and in the control of the newly introduced dynamics due to the moving plates.
A start-up is exploring how to bring current technology to the market, in cooperation with partners in industry, while Delft University of Technology will continue to research next generations of this highly innovative concept. ■

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[4] Waferstage with high precision linear optical encoders: www.youtube.com/watch?v=_LkeUkm5d9E
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