SIX-DEGREE-OF-FREEDOM PLANAR POSITIONER WITH LINEAR MAGNETIC BEARINGS/MOTORS

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ABSTRACT

This paper presents a planar positioner with linear magnetic bearings/motors. This positioning system is the first capable of providing all the motions required for photolithography in semiconductor manufacturing with only a single moving part, namely the platen. The single moving part generates all six-degree-of-freedom (6-DOF) motions required for focusing and alignment, and large two-dimensional motions (50 $\times$ 50 mm) for positioning. Four linear permanent-magnet motors/bearings produce suspension forces to support the platen (5.58 kg) as well as driving forces. We also demonstrate that it follows a 20-mm step motion command in only 120 ms. The stage has nanometer-order position stability and the design can be readily scaled for the next generation of photolithography.

INTRODUCTION

The control of motion in the near-vicinity of a plane is an important task in many precision machines, for example, wafer steppers, surface profilometers, and scanned probe microscopes. In the case of wafer stepper stages, which are the primary focus of our work, the motion control stage must provide travel over relatively large displacements (on the order of hundreds of millimeters) in two planar degrees of freedom, small displacements (on the order of hundreds of micrometers) in the direction normal to the plane, as well as small rotational displacements (on the order of milliradians) about three orthogonal axes.

Figure 1 shows how a wafer stepper works. The wafer stepper is operated in step, expose, and repeat sequence to position the wafer under the lens for lithography. The die site on the wafer is exposed by patterned ultraviolet light as defined by the mask. The one-step distance depends on the dimension of the die sites whose typical lateral dimension is on the order of 20 mm. As the time duration for moving the wafer from one die site to another heavily affects the throughput, faster positioning speed is desirable. In steppers, a die site under the lithographic lens is exposed while the wafer is at a standstill. There are also advanced step-and-scan type lithography tools where exposure occurs on the fly

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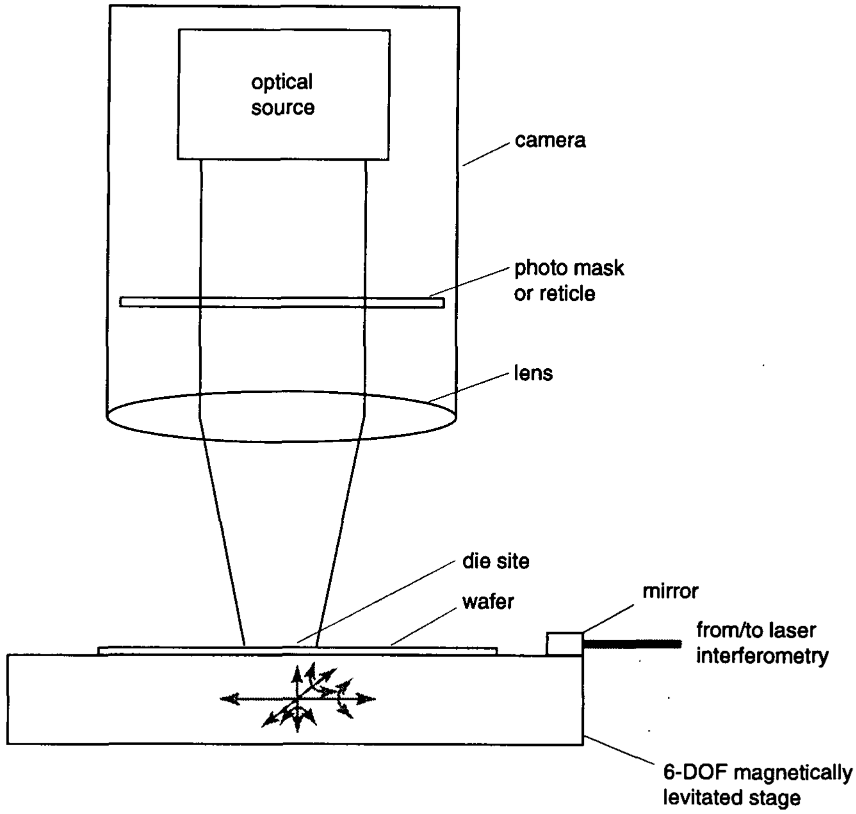

Figure 1: Schematic wafer stepper realized with a six-degree-of-freedom magnetically levitated stage

(Buckley, Galburt and Karatzas, 1989). So, precise position control is very important in the current and future deep-submicron lithography technology.

Figure 2 shows our prototype six-degree-of-freedom planar positioner with linear magnetic bearings/motors. The stage position in the plane is measured with three laser interferometers with sub-nanometer resolution. The stage position out of the plane is measured by three capacitance gages with nanometer resolution. At present, the stage is operational with a positioning noise of 5 nm rms in x and y, and is demonstrating acceleration capabilities in excess of 1 g (10 m/s^2). The positioning range of this stage is 50 mm $\times$ 50 mm in a plane, 400 μm normal to the plane, and milliradian rotation about each of the three translational axes.

This paper presents the working principles underlying the positioner operation, and experimental data demonstrating its performance capabilities. In the following section, the structure of the linear magnetic bearing/motor is described. The overview of the six-degree-of-freedom planar positioner is given, and test results are presented and discussed.

LINEAR MAGNETIC BEARING/MOTOR

The platen is the only moving part of the levitator system. It is intended to carry a wafer in real applications, so other devices to hold and transport wafers, such as vacuum

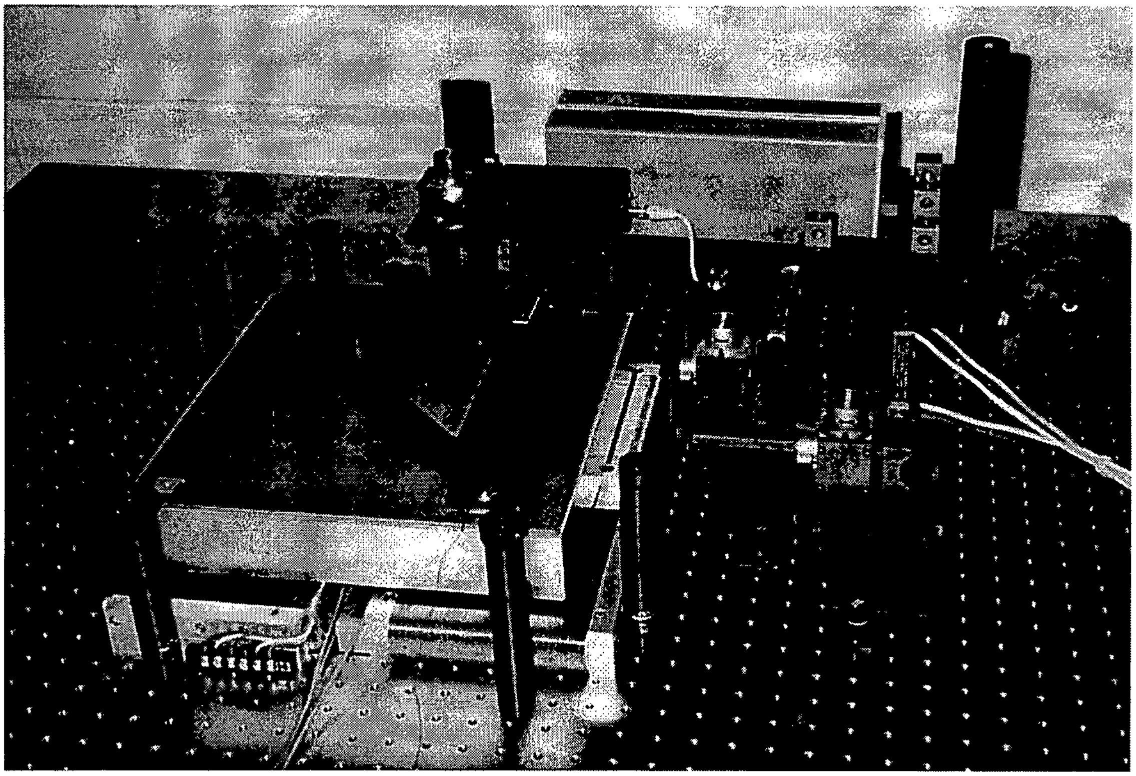

Figure 2: Prototype six-degree-of-freedom planar positioner with linear magnetic bearings/motors

chucks, are needed in a final design. Such detailed supporting mechanisms are neglected in this prototype. The prototype platen has magnet arrays as parts of the linear magnetic bearings/motors and also carries metrology devices such as a square mirror and capacitance gage targets. Figure 3 shows the bottom view of the platen after the magnet arrays are placed.

Thirty-three Gramme windings (racetrack-shape) are stacked to form the linear motor stator. Each of the three phases consists of eleven such windings in series. One winding has fifty-four turns with heavy-build AWG#23 resistance-bondable wire. Using the analytical work presented in (Trumper, Kim and Williams, 1996), the electrical ratings of the linear motors are determined as follows: phase = 3, phase inductance = 3.44 mH, phase resistance = 14.4 Ω, nominal phase current = ±0.5 A, maximum phase current = ±1.5 A, nominal phase voltage = ±7.2 V, maximum phase voltage = ±22 V. Figure 4 is the top view of a stator with its associated capacitance probe after the winding assembly.

For our three-phase permanent-magnet linear motors, the parameters have the following values: magnet remanence $\mu_0 M_0$ = 1.29 T, pitch l = 25.6 mm, and the nominal motor air gap z_0 = 250 μm. The magnet array thickness is $\Delta = l/4$ and the winding thickness is $\Gamma = l/5$. To drive the motors, we implement linear transconductance power amplifiers, with maximum current and voltage ratings of ±1.5 A at ±22 V (Kim, 1997). The nominal power dissipation per motor required to carry the stage weight is 5.4 W at the 0.5-A nominal peak phase current. The total suspension power coefficient of the stage is thus 7.2 mW/N^2.

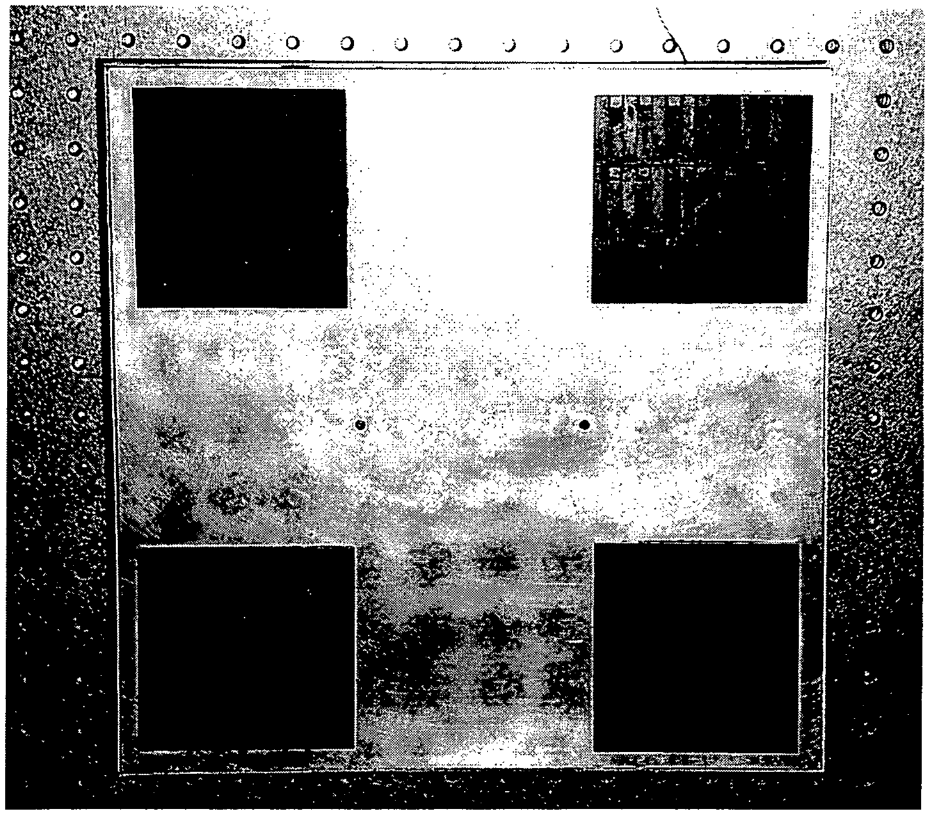

Figure 3: Bottom view of the platen

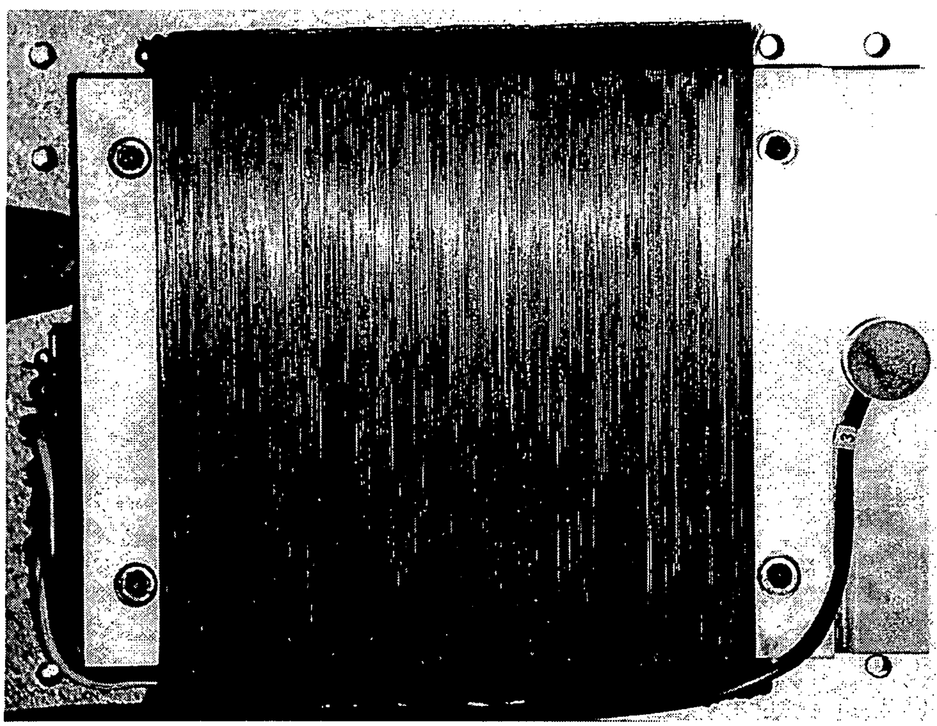

Figure 4: Top view of a motor stator with a capacitance probe mounted on its rail

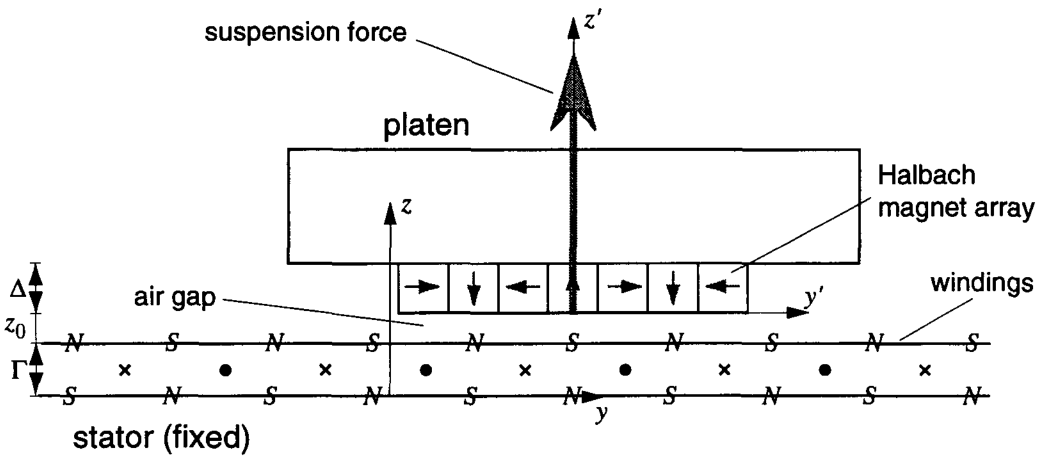

Figure 5: Suspension of the platen in dynamic equilibrium. Only peaks of winding currents are indicated as dots and crosses.

Figure 5 depicts the dynamic equilibrium around which the levitator operates and is stabilized. The stator currents are shown as x's into the page and •'s out of the page. We also show the north (N) and south (S) poles generated by these currents. At a fixed time, if we generate the current sinusoidally distributed in the y-direction as in Figure 5, there is vertical repulsive force between the same magnetic poles of the magnet array and the current distribution (i.e., corresponding north to north and south to south). This vertical repulsive force lifts the platen against gravity. Since this equilibrium is unstable in the lateral direction (in the y-direction in the figure), however, we need active feedback control to stabilize the motion of the platen around this dynamic equilibrium. Conceptually, we can control the magnitude of the force by changing the magnitude of the current, and direction of the force by commutation. See (Kim, 1997; Trumper, Kim, and Williams, 1996) for more details.

PLANAR POSITIONER OVERVIEW

The magnetic levitator contains four three-phase linear permanent-magnet motors as labeled in Figure 6. Each linear motor can generate suspension (vertical) force as well as drive (lateral) force (Trumper, Kim and Williams, 1996). These four linear permanent-magnet motors collaboratively produce suspension forces to support the platen against gravity as well as drive forces. With an orthogonal arrangement of the motors as in Figure 6, the platen generates all 6-DOF motions for focusing and alignment and large two-dimensional step and scanning motions for a high-precision positioner as a wafer stepper stage in semiconductor manufacturing.

Combinations of the actuator forces, rather than a single motor, generate a translational or rotational motion. For instance, two of the motors (I and III) drive the stage in the x-direction, and the other two (II and IV), in the y-direction. The motor forces are coordinated appropriately to control the remaining degrees of freedom. We can allocate three lateral modal forces to four lateral motor force components by the following modal

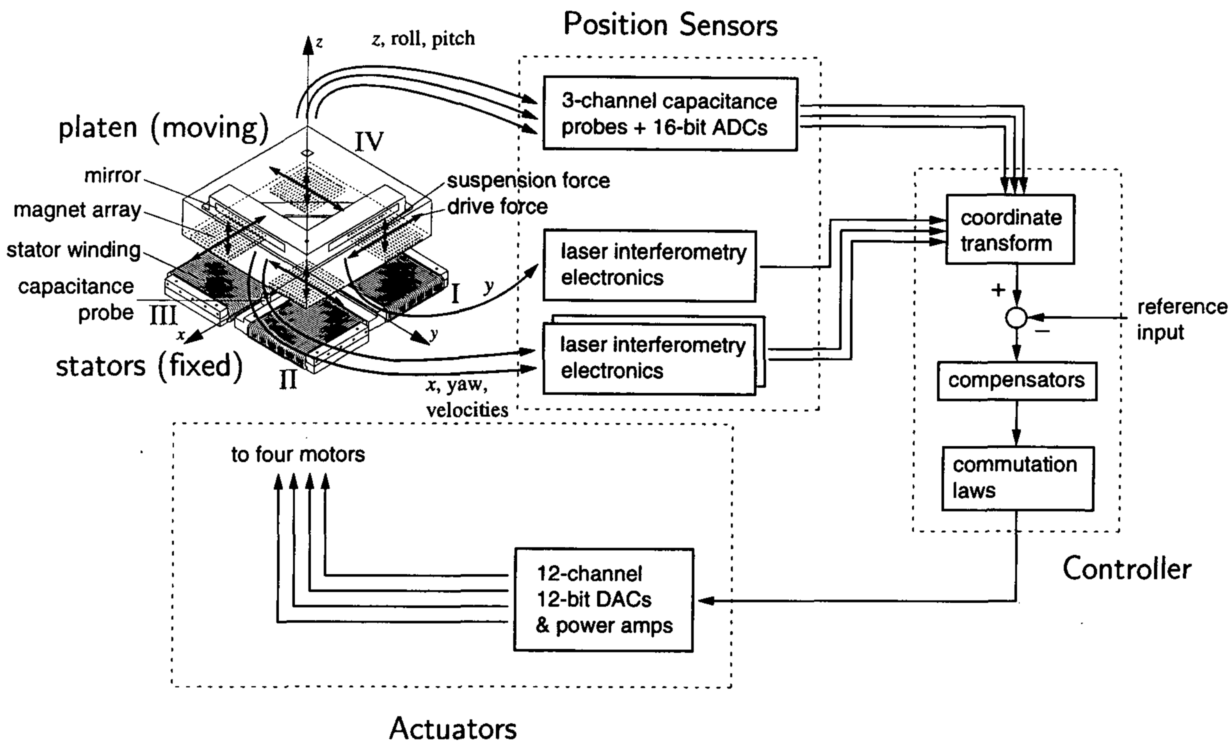

Figure 6: Control loop

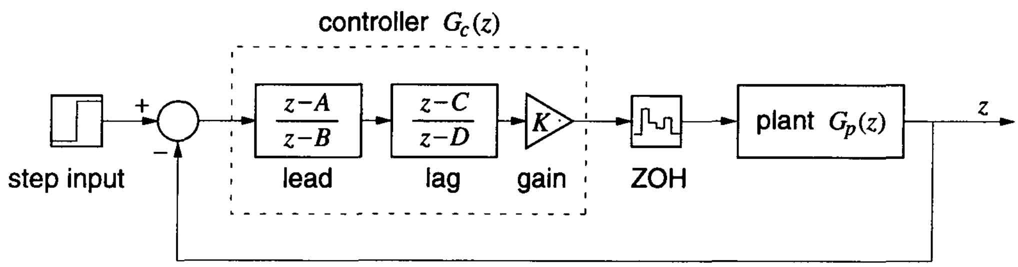

Figure 7: Decoupled lead-lag digital controller

force transformation (Kim, 1997).

$$\begin{bmatrix} f_{1x} \\ f_{2y} \\ f_{3x} \\ f_{4y} \end{bmatrix} = \begin{bmatrix} 0.55509 & 0 & 0 \\ 0 & 0.55509 & 4.9225 \\ 0.44491 & 0 & 0 \\ 0 & 0.44491 & -4.9225 \end{bmatrix} \begin{bmatrix} f_x \\ f_y \\ \tau_z \end{bmatrix} \tag{1}$$

The elements in the transformation matrix depend on the motor geometry and the location of the platen center of mass. Since we have four lateral motor force components (f_{1x}, f_{2y}, f_{3x}, and f_{4y}) to generate three modal forces (f_x, f_y, and τ_z), however, this force allocation has one arbitrary degree of freedom.

Figure 7 is a block diagram of the discrete-time lead-lag controller with $A = 0.96300$, $B = 0.68592$, $C = 0.99624$, and $D = 1$. The gains K for the six axes, x, y, z, ψ, θ, and ϕ are 2.2261×10^6 N/m, 2.2261×10^6 N/m, 2.3141×10^6 N/m, 2.2504×10^4 N/rad,

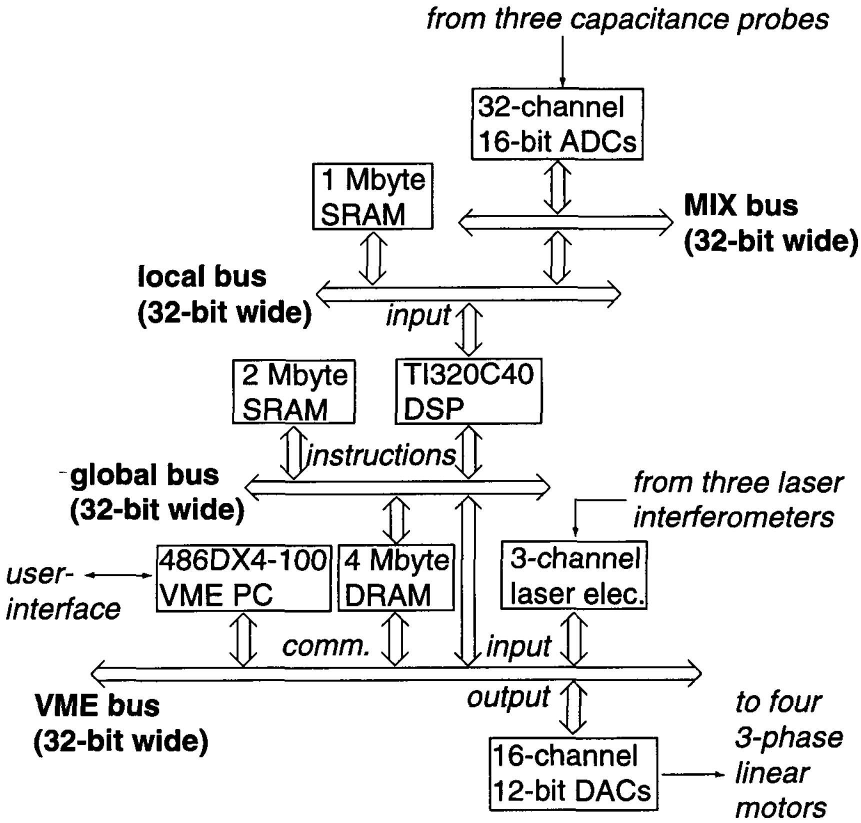

Figure 8: Instrumentation structure

2.2504×10^4 N/rad, and 3.9804×10^4 N/rad, respectively. For small angular motions in our levitator, the Euler angles ψ, θ, and ϕ can be considered as rotational angles around the x-, y-, and z-axes, respectively (Goldstein, 1980). Because of the geometrical symmetry in x and y of the levitation system, they have identical controllers. The same is true for the controllers for ψ and θ.

Control algorithms are implemented digitally in a Pentek 4284 board based on the Texas Instrument TMS320C40 digital signal processor. A Radisys 80486-100 MHz VME PC takes care of the user interface, such as monitoring levitator state variables and command interpretation. The PC and the digital signal processor communicate with each other over the VMEbus using dual-port shared RAM residing on the Pentek 4284 board. On the VMEbus exist three channels of Hewlett-Packard 10897A laser axis boards for horizontal motions and a DATEL DVME-622 12-bit D/A converter board. There is a MIXbus local to the digital signal processor connected to a Pentek 4245 16-bit A/D converter board. We have three ADE 3800 systems including three ADE 2810 capacitance probes for vertical motions. The output ranges of the ADE 3800 systems are modified to be ± 7.5 V to match the input voltage swing of Pentek 4245 A/D converter board. Figure 8 shows the instrumentation structure for the system.

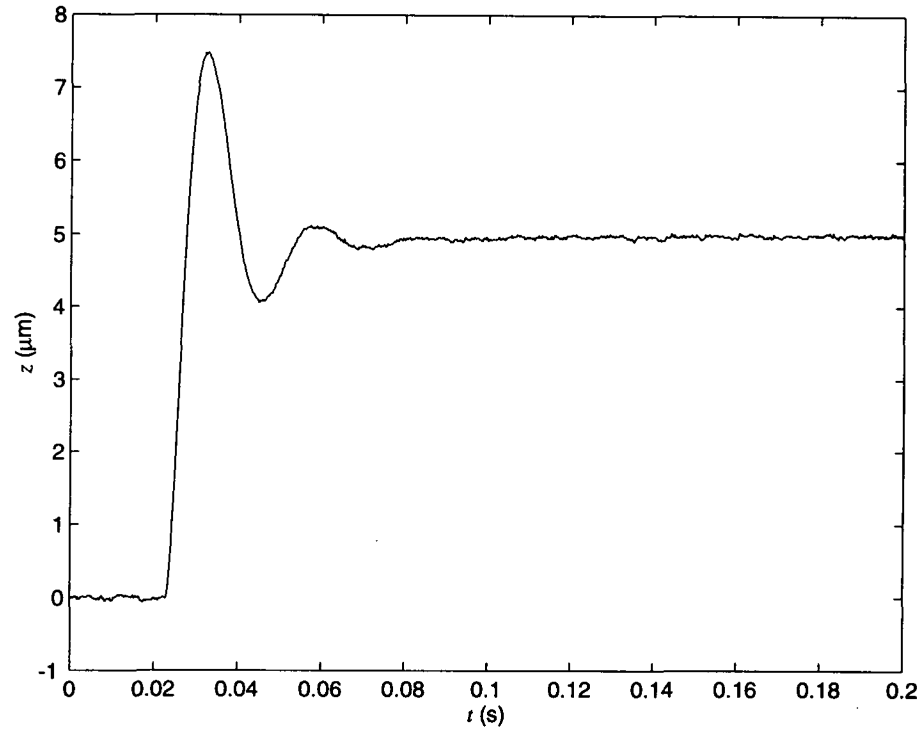

Figure 9: 5-μm step in z

TEST RESULTS

We present test results in this section. Figure 9 shows a 5-μm step response in z with the above lead-lag compensators. All the six-axis controllers are operational in this experiment. The sampling frequency is 5 kHz and the loop cross-over frequency is 50 Hz. It shows a typical step response of a second-order system with damping ratio, $\zeta = 0.5$ as designed.

For fast motion generation, we accelerate the platen at the highest acceleration possible until the velocity reaches the maximum slew rate, hold this velocity for a while, then decelerate the platen at the same maximum acceleration to brake the platen motion. This is called a trapezoidal velocity profile. The platen thus follows a parabolic, a linear, and another parabolic reference trajectories. Figure 10 is a test result with a 20-mm step in the y-direction. The acceleration given to the platen is 10 m/s^2 (about 1 g). The command follows a 120-ms transition time for the 20-mm step.

CONCLUSIONS

We have designed and implemented the world's first six-degree-of-freedom planar positioner with linear magnetic bearings/motors for photolithography in semiconductor manufacturing. The magnetically levitated platen generates all the required small motions for focusing and alignments as well as large planar motions for wafer positioning. This

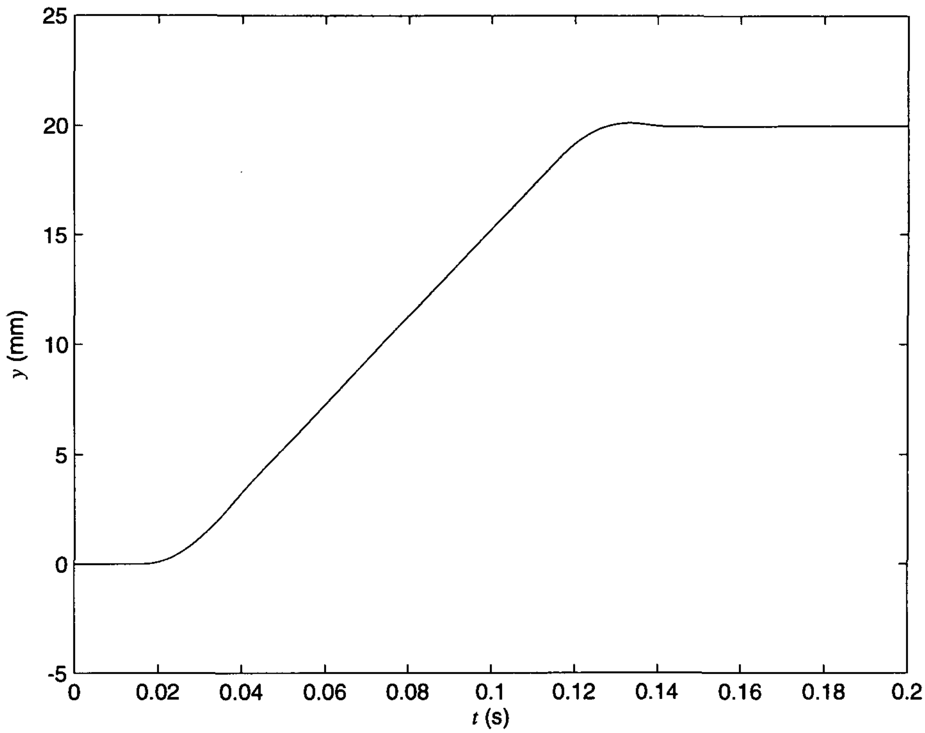

Figure 10: 20-mm step in y. The platen follows a trapezoidal velocity profile.

planar positioning stage has been tested successfully. We implemented decoupled lead-lag digital controllers in a 320C40 digital signal processor. The sampling rate of the system is 5 kHz. Important experimental achievements include 5-nm rms position error in x and y, 30-nm rms position error in z, 20-mm steps following 120-ms references, and 1-g acceleration. We thus have demonstrated that the six-degree-of-freedom planar positioner with linear magnetic bearings/motors is a promising candidate as the positioning stage in next-generation semiconductor manufacturing.

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