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MAGLEV SIX DEGREE-OF-FREEDOM FINE POSITION STAGE CONTROL SYSTEM

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ABSTRACT

A wafer positioning system was recently developed by Sandia National Laboratories for an Extreme Ultraviolet Lithography (EUVL) tool[1]. The system, which utilizes a magnetically levitated fine stage to provide ultra-precise positioning in all six degrees of freedom, incorporates technological improvements resulting from four years of prototype development experience. System enhancements, implemented on a second generation design for a National Center for Advanced Information Component Manufacturing (NCAICM) Structural Control Testbed, define the present level of research.

This paper describes the design, implementation, and functional capability of the systems. Specifics regarding control system electronics, including software and control algorithm structure, as well as performance design goals and test results are presented.

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*[1] The EUVL and NCAICM programs, including the subject positioning systems, being performed at Sandia National Laboratories, is supported by ARPA DALP and by the US Department of Energy under contract DE-AC04-94AL85000.

INTRODUCTION

Magnetic levitation (maglev) is emerging as an important technology for wafer positioning systems in advanced lithography applications. The advantages of maglev stem from the absence of physical contact. The resulting lack of friction enables accurate, fast positioning. Maglev systems are mechanically simple, accomplishing full six degree-of-freedom suspension and control with a minimum of moving parts. Power-efficient designs, which reduce the possibility of thermal distortion of the platen, are achievable. Manufacturing throughput will be improved in future system with the addition of active structural control of the positioning stages.

History of Maglev Positioning at Sandia

In the late 1980s, a concept for a magnetically levitated fine positioning technique was developed at MIT by Dr. David Trumper. GCA Corporation viewed this new technology as very promising for lithography applications. Barriers to this plan included several difficulties in the application of the technology, such as the nonlinear aspects of the actuators and implementation of the multi-input, multi-output control strategy required. These difficulties prompted GCA and SEMATECH, through the Sandia/SEMATECH Cooperative Research and Development Agreement (CRADA), to seek assistance from Sandia in the development of a maglev fine stage control system. The first part of the Sandia effort was the development of a control system for a prototype maglev fine stage. By the time of GCA's demise in mid-1993, proof-of-concept testing of the stage system had been successfully accomplished at Sandia.

The ARPA Advanced Lithography Program funded a study that specified control system improvements for commercial application. Knowledge gained during these efforts were applied to the development of the wafer stage system for the EUVL program. Further improvement of the system has been achieved during the implementation of a National Center for Advanced Information Component Manufacturing /ARPA funded Structural Control Testbed (SCT) project for integrated circuit lithography. Currently, through a CRADA with Integrated Solutions, Inc., Sandia is assisting in the development of a commercial version of a maglev wafer positioning system.

The EUVL Project

The demand for smaller critical dimensions in integrated circuits has driven projection lithography to shorter wavelengths. Research and development to extend this trend to extreme ultraviolet (EUV) wavelengths, in the range of 11 nm to 14 nm, is underway at Sandia National Laboratories in Livermore, California. An EUVL laboratory tool using a 10x reduction Schwarzchild camera and magnetically levitated wafer stage driven by a digital feedback controller facilitate this research. The Sandia system[1] (Figure 1) is the first attempt at integrating all major subsystems into an EUVL laboratory tool suitable for device fabrication experiments. Further development of EUV technology is aimed at the goal of building a practical lithography tool capable of producing microelectronics devices having critical dimensions of less than 0.13 μm.

Structural Control Testbed Project

The structural control testbed (Figure 2) project incorporates active structural control (ASC) into the maglev wafer positioning system. This design utilizes knowledge gained during the EUVL system development to optimize system bandwidth. It effectively raises the performance of the control system, both hardware and software, to a level that shifts system limitations to the structural components of the machine.

The great expense of the fabs required for integrated circuit manufacturing motivates the emphasis on positioning speed. Increasing fab throughput by increasing the speed of the processing equipment is an economic necessity. For lithography exposure tools, this means minimizing the time spent positioning the wafers between exposures. Unfortunately, regardless of the positioning mechanism, there is a positioning speed limit where further increase in speed results in excitation of structural resonances that degrade accuracy to below acceptable levels. This program develops an active method of structural resonance cancellation.

SYSTEM REQUIREMENTS

EUVL

The EUVL system[3] must provide a highly stable and accurate platform for the successful imaging of 0.1 micron features. It requires a limited positioning range. The coarse stage travel is limited to ± 37 mm in the Y axis and ± 50 mm in the X axis, X and Y being horizontal axes, in the plane of the wafer. The coarse stage is controlled to position the center of the fine stage to within 2 μm of the final position. The fine stage is accurate over a ±150 μm range in both X and Y-axes. The positioning system must be capable of holding a target wafer sufficiently still to allow creation of a 100nm feature with no appreciable smearing. For this implementation, X/Y positioning noise of up to 10nm p-p (at a high probability) of X/Y image motion was deemed acceptable. Absolute position errors of less than 10nm at 3 sigma for 1 cm travel are required.

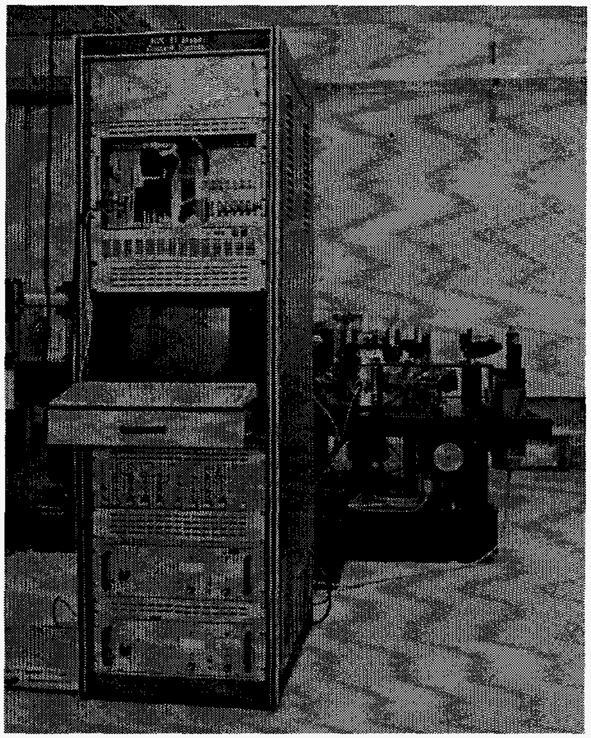

Figure 1. The EUVL positioning system.

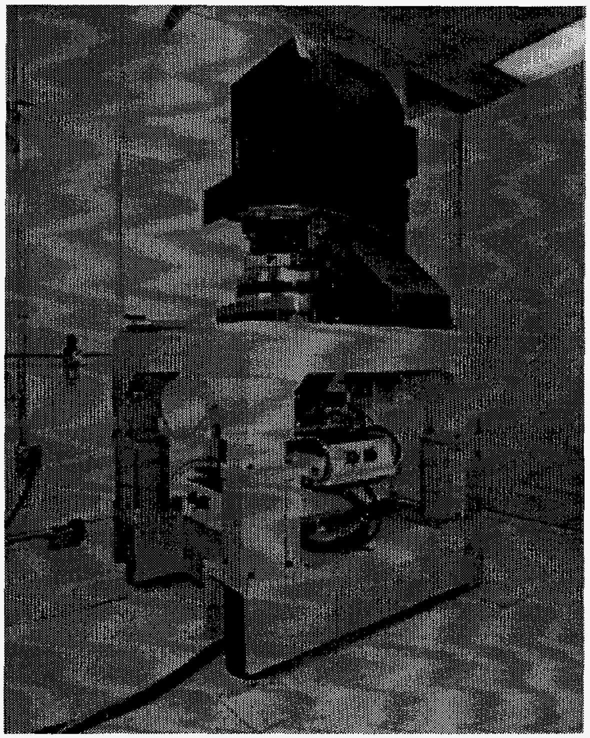

Figure 2. The Structural Control Testbed.

The stage control system must be able to communicate with the EUVL executive computer system. It also must provide the interface to the grazing incidence focus system and indirect alignment system. The stage assembly and position measuring laser interferometers reside in a vacuum chamber. All mechanical and electrical components of these assemblies must be compatible with vacuum operation. The system must provide a Z axis resolution comparable to that of the X and Y axes in order to accurately return a wafer to within ½ wavelength of a position previously established. This requirement necessitates a dual focus methodology that includes a "coarse" focus system for repositioning a wafer and an interferometrically controlled "fine" position system to maintain the position accuracy and stability required.

The requirements for positioning bandwidth (a measure of the positioner's repositioning speed used to indicate wafer throughput capability) are liberal due to the research nature of the tool. A 30 Hz bandwidth is acceptable. The control rate is 2500 Hz in the EUVL system.

Structural Control Testbed

The requirements of the SCT are to increase the throughput of a lithography stepper while maintaining the positioning stability and accuracy described for the EUVL project. The desired increase in bandwidth is 5 to 10 times the present 30 Hz. This is to be accomplished by hardware and software inprovements and the addition of active structural control.

The active structural control approach relies on auxiliary sensors and actuators, embedded in the platen, for resonance suppression. The sensors are connected to piezoelectric actuators through a control system, which drives the actuators to oppose the influence of the resonance. Active structural control has the advantage of being able to adapt as resonances change frequency during different phases of machine operation.

SYSTEM CONFIGURATIONS

The wafer positioning system for the EUVL research tool consists of the maglev stage, two long travel coarse position stages, an electronics rack and a high resolution interferometry system. The Structural Control Testbed differs from the EUVL system in that it utilizes an additional DSP system to control the structural resonances of the levitated platen. The Structural Control Testbed is assembled on commercial positioner base and bridge.

Maglev Fine Stage

The design of the maglev fine stage for the EUVL system is essentially unchanged from that originally developed by GCA and MIT[2] (Figure 3). The stage consists of the levitated aluminum (SCT) fine stage platen containing sixteen ferrous targets and the interferometer mirror, the frame holding the sixteen E-core electromagnets and six capacitive position sensors. Since 1993, extensive refinements have been applied to the electronics and software used to operate and control the system and to provide interfaces required by the EUVL and NCAICM systems.

Interferometry

A Hewlett Packard Laser interferometry system consisting of five interferometers, two laser sources, beam benders, optical receivers, and high resolution laser axis boards provide position information in all six degrees of freedom. The interferometry can resolve to 0.625nm in X and Y and 1.25 nm in Z (EUVL). The Z axis requires that a wafer be in place to provide a reflecting surface for the light beam.

Capacitive "Gap" Sensing

The maglev fine stage utilizes six capacitive sensors for determination of the "gap" between the movable platen and stationary frame. This information is used to linearize the maglev actuator force characteristics for control purposes. The fine stage can be controlled and positioned using only these sensors for feedback, but with less accuracy than that obtainable with the interferometers.

Electronics

Two computers are used in the implementation of the wafer positioning system. An embedded VME-based 486 PC provides the user interface. The electronics include seven (six for EUVL) TMS320C40 DSPs for data acquisition, manipulation, and control. Figure 4 is a diagram showing the major system elements. The host computer is an embedded PC subsystem that mounts in the VMEbus chassis. It provides a critical interface between the operator and the positioning system. A user can access the system using a monitor and keyboard or TCP/IP network interface.

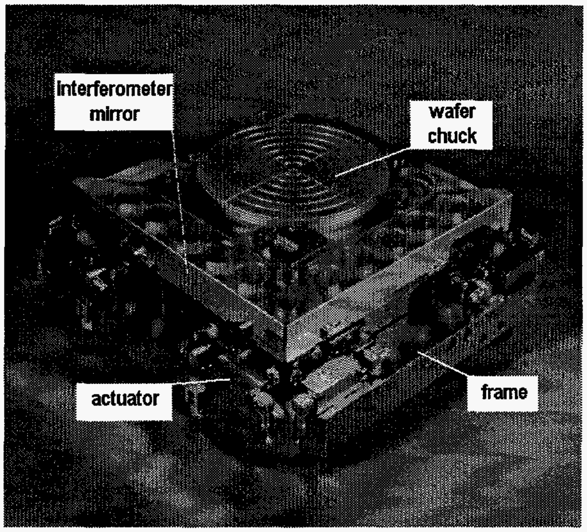

Figure 3. The maglev fine stage.

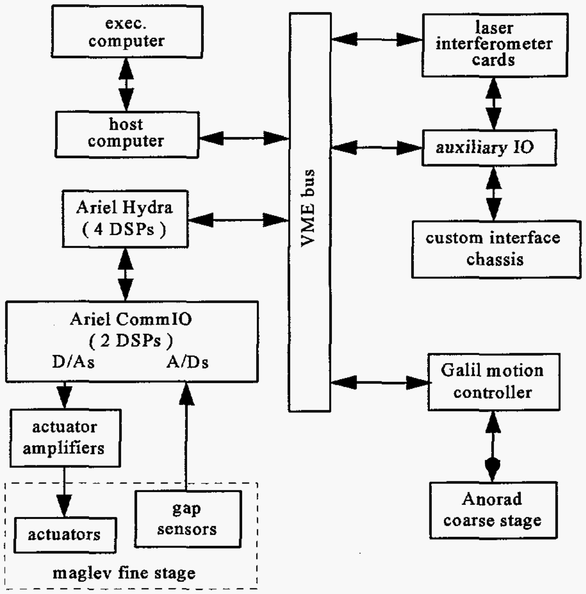

Figure 4. Positioning system block diagram.

The digital signal processing computer consisting of four TMS320C40 DSPs located on a Ariel Hydra™ computer board and three (two for EUVL) additional TMS320C40 DSPs on Ariel CommIO-IP™ interface boards. Analog-to-digital I/O is used to gather gap information from the capacitive sensors as well as other miscellaneous system data. Sixteen channels of digital-to-analog I/O control the current amplifiers which drive the electromagnetic actuators.

Custom electronics are provided for interfacing the components of the coarse and fine stage to the computer electronics. The chassis includes power supplies, enabling relay circuitry, I/O analog filtering, and interface matching circuitry.

In the EUVL the two coarse stages are controlled using a dedicated control computer (Galil DMC1320). The coarse stage of the SCT are controlled via the DSPs.

Custom current amplifiers are used to supply drive current to the sixteen electromagnetic actuators. They are 1 amp limited, but capable of up to 100 volts output. This provides the inductive magnetic actuator with a fast force response thereby allowing high bandwidth positioning.

CONTROL SYSTEM DESIGN

The controller decomposes the large problem of positioning the fine stage platen into six smaller, independent problems. Each of the three linear positions of, and three angular rotations about, the center of mass are treated separately. This means that the sensor information must undergo a linear transformation (matrix multiplication) to provide the desired measurements. Once the deviations from the desired positions are known, the forces and torques required to drive them to zero can be computed.

There are six independent compensators running in 'C40 assembly language to accomplish this task. Each compensator is a proportional-integral-derivative (PID) controller and additionally has notch filters for dealing with structural resonances. Once the desired forces and torques are known, the sixteen actuator forces that will generate them must be computed. This is accomplished by another transformation. Once the individual desired actuator forces are known, the currents required to produce them must be calculated. The force in each actuator is a nonlinear function of the current flowing in the actuator and the gap between the E-core electromagnet in the frame and its corresponding target in the platen. First, the gap at each actuator must be computed, which is done by a linear transformation of the capacitive sensor measurements. The nonlinearity can then be computed, directly for moderate forces, and using a lookup table for larger forces, when the actuator is approaching saturation. A complete simulation of the system was constructed using the Matlab Simulink™ environment. Included in the simulation are the dynamics of the levitated platen, the nonlinearities associated with the actuators, the voltage limitations associated with the transimpedance amplifiers, quantization errors, computational delays associated with the control computer, and changes in the interferometer measurement equations due to displacement of the platen. A simplified model of the coarse stage is also included. Figure 5 shows a block diagram of the controller used in the structural control testbed.

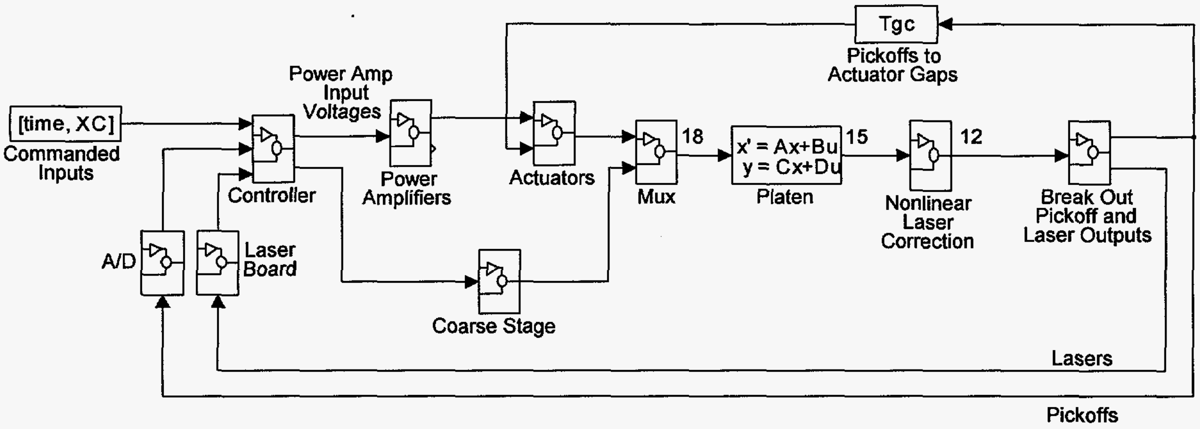

Figure 5. Controller block diagram.

For the EUVL system, a commercial controller was used to control the coarse stage. The strategy used to move the coarse and fine stages was to center the platen in the frame using the capacitive sensors and issue a command to the commercial controller. When it completed its move, the platen would be commanded to the appropriate position using the laser interferometers. This two-step procedure was satisfactory for a laboratory tool, but a production machine would require higher speed moves and tighter integration of the coarse and fine motions. In the NCAICM system, the coarse stage controllers are run on the DSP board alongside the fine stage controllers. The position of the coarse stage is computed by monitoring the absolute position of the platen using the interferometers and the relative position of the platen in the frame using the capacitive sensors. When a move that is outside the range of the fine stage is required, a nearly time-optimal move trajectory is computed. The coarse and fine stages are commanded to move along that trajectory simultaneously. The best response is accomplished by computing the acceleration required during each phase of the trajectory, what forces are needed to produce this acceleration, and then adding these forces directly to those computed using the feedback controllers. This feedforward strategy enabled move accelerations up to one g.

SOFTWARE DESIGN

The Stage Control System software requirements are very broad. Several different pieces of hardware have been integrated and controlled. The through-put of the system is sufficiently high in order to decrease control system phase delays. The user interface is flexible enough to allow easy system development, user control, and system diagnostics.

The Stage Control System software is made up of C and assembly language written and compiled for use on 486 PC and TMS320C40 processors. Additionally, a text based language is used for programming the Galil motion control board. Vendor supplied board specific routines are used where possible. Each DSP of the Hydra and the CommIO-IP boards execute distinct programs allowing individual processor task tailoring. Controller timing, controller synchronization, and system state are controlled by one of the seven DSPs.

Host Software Structure/Function

The Host PC software is responsible for several aspects of the system. It handles system startup and initialization sequences, user interface functions, EUVL executive computer communications, coarse stage controller interface, and system data collection and analysis.

The user interface running on the Host PC is based on a set of commands and the DSP address map that is built at startup. The Host PC loads a command and its associated data in the shared RAM on the Hydra, or dual port ram on the CommIO IPs, sets a flag, then waits for a response from the particular DSP being commanded. Any address available to any DSP in the system is also available for reading or writing by the Host PC through the interface All user interface functions are low priority tasks.

Data Collection and System Diagnostics

All data collection and system diagnostics are coordinated by the Host PC. The user, through the user interface, can configure the DSPs on Hydra to capture “snapshots” of real time data of interest. The “snapshot” is triggered by a system command or user input allowing flexible performance monitoring and system diagnostics. The “snapshot” data can then be transferred to the Host PC and written to disk or loaded directly to Matlab™. The user interface screen displays important controller and system data which is automatically updated once per second.

A direct interface to Matlab has been developed allowing for graphical system performance monitoring, modal analysis, and controller parameter adjustments. Controller parameters for all six modal axis and coarse stages, such as sample rate, plant inertia, bandwidth, damping, and up to ten output notch filters per axis, can be defined. The controller coefficients based on these parameters are automatically generated and downloaded to the system allowing controller modification “on the fly”.

The DSP software is primarily responsible for executing the fine stage and coarse stage controller tasks. These tasks include gathering position sensor data, executing controller algorithms, and outputting to actuators. The DSP software also must initialize hardware under its control at startup, handle error situations, and deliver data to the Host PC when commanded.

System Control Tasks

After the system has been initialized, the DSP software begins executing the control loop as described under "Control System Design". The controller tasks are distributed among the four DSPs on Hydra and the three DSPs on the CommIO-IPs to maximize system through-put. Much of the sequence occurs in parallel. The entire control loop is executed in less than 125μs yielding a sample rate of 8Khz.

The control loop timing is generated by an internal timer of the master DSP. The timer generates an interrupt to the master DSP at a programmable rate. When the master DSP services the interrupt, it transmits commands over the communication ports to the other DSPs signaling the beginning of a cycle, thus synchronizing the four processors. All controller data are passed between processors via the C40 communication ports which give complete interconnectivity between the seven processors.

The controller difference equations and filters are implemented as infinite input response filters (IIR) with cascades of second-order sections (biquads). This implementation allows the controller algorithms and output filtering to be executed very quickly utilizing the C40's circular buffering, zero overhead looping, and parallel instruction capability. There are twenty-nine IIR filters in the SCT system.

PERFORMANCE TESTING RESULTS

For the EUVL system the standard deviation of the distance of the image from the desired location on the wafer surface is less than 2.5nm ($\sigma < 2.5$nm). During exposures, when there is generally more activity in the clean room and more equipment running, it is 3nm $< \sigma <$ 4nm. The EUVL project team was able to demonstrate 0.1 micron lithographic-quality features with operational positioning stability of $\sigma \approx 4$ nm.

The overall system accuracy has not yet been determined. The next set of experiments on the EUVL project will entail overlaying one exposure on top of another. The absolute positioning accuracy will be very important for these experiments.

As mentioned previously, the EUVL fine stage positioning bandwidth is 30 Hz. The bandwidth of the SCT was raised to 90 Hz by incorporating a number of changes to support the required increase in sample frequency (from 2500 Hz to 8000 Hz). With a 90 Hz bandwidth, high frequency positioning noise was 5 nm peak-to-peak. Further increases in bandwidth resulted in unacceptable levels of high frequency noise due to excitation of structural resonances. For example, at a bandwidth of 150 Hz, positioning noise was about 250 nm (25 times the acceptable level).

Active control of the platen structural resonances was added to enable the use of a 150 Hz positioning bandwidth. Using finite element analysis, the locations for three PZT actuators were chosen to be optimal in terms of resonance control effectiveness. After installation in the platen, one actuator was used as a sensor and one was driven via a DSP-based controller board. The most troublesome resonance was suppressed, resulting in positioning noise of only 5nm.

For a 1 micron fine stage step, settling time was reduced from 10 ms without structural control (90 Hz bandwidth) to 6 ms with structural control (150 Hz bandwidth). Sandia expects to accomplish even shorter settling times by using each piezo element as both sensor and actuator. The collocation of sensor and actuator enables suppression of specific resonances without exciting others.

SUMMARY/CONCLUSIONS

Integrated circuit manufacturing technology must improve at a rapid rate to meet the challenge of future requirements for smaller feature sizes and larger wafers. A wafer positioning stage using magnetic levitation and active structural control has been developed and used to demonstrate accuracy and speed characteristics which are consistent with these requirements. This advancement in the state-of-the-art was enabled by recently developed multi-DSP electronics and software.

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