SAND2000-0227C

Wafer and Reticle Positioning System for the Extreme Ultraviolet Lithography Engineering Test Stand

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ABSTRACT

This paper is an overview of the wafer and reticle positioning system of the Extreme Ultraviolet Lithography (EUVL) Engineering Test Stand (ETS). EUVL represents one of the most promising technologies for supporting the integrated circuit (IC) industry's lithography needs for critical features below 100nm. EUVL research and development includes development of capabilities for demonstrating key EUV technologies. The ETS is under development at the EUV Virtual National Laboratory, to demonstrate EUV full-field imaging and provide data that supports production-tool development. The stages and their associated metrology operate in a vacuum environment and must meet stringent outgassing specifications. A tight tolerance is placed on the stage tracking performance to minimize image distortion and provide high position repeatability. The wafer must track the reticle with less than ±3nm of position error and jitter must not exceed 10nm rms. To meet these performance requirements, magnetically levitated positioning stages utilizing a system of sophisticated control electronics will be used. System modeling and experimentation have contributed to the development of the positioning system and results indicate that desired ETS performance is achievable.

Keywords: EUVL, maglev, stages, lithography, positioning system

1. INTRODUCTION

The EUVL vacuum environment and unique properties of EUV projection place challenging requirements on the stage system. It must operate in scanning mode with constraints imposed by system nontelecentricity at the reticle. Heat generation must be minimized to assure a stable thermal environment. All in-vacuum components must be fabricated to minimize outgassing and control contamination of the ETS environment. Particle generation and power dissipation must be minimal to prevent distortion during the printing of critical IC features. Stage-to-stage position control must equal current high-end lithography tool performance, and the stages and electronics must be highly reliable and require little maintenance. These requirements have resulted in a stage subsystem design that combines common stage control methodology with the unique challenges of in-vacuum operation. Magnetically levitated (maglev) stages have been chosen as the lowest-risk approach to addressing the power and vacuum requirements. State-of-the-art computer control hardware and software are used to synchronize scanning of the reticle and wafer stages. The overall ETS system has been modeled as part of the development process to assess design viability and aid in final system analysis. Testing of the prototype wafer and reticle stages indicates that the stage system will meet ETS performance specifications. This paper will describe the maglev stages, the subsystem in which they reside, the stage control architecture and implementation, the system modeling, and current performance results.

2. STAGE SUBSYSTEM CONFIGURATION

The wafer and reticle stage subsystem consists of: the reticle stage, wafer stage, reticle chuck, wafer chuck, metrology trays for each stage, control electronics, and the stage support bridge. The wafer and reticle stages are mounted to the bridge approximately 1 meter apart and the bridge is attached directly to the grounded frame of the machine body. The metrology trays and projection optics box (PO box) are supported in a structure known as the isolated frame which is isolated from floor motion by actively damped, passive vibration isolators. All stage positions are referenced to the PO box or the isolated metrology frame, and the stage control forces are referenced to the bridge. This architecture is common in state-of-the-art

Deep-UV step-and-scan systems and shunts stage control forces directly to ground. Shunting the control forces to ground prevents internal vibrations of the PO box and other sensitive structures.

The in-vacuum components of the positioning system are the wafer and reticle stages, interferometers, stage support structures, *X* and *Y* position reference mirrors, stage position initialization sensors, focus sensors, the isolators and isolated frame, and electrical cables. These components are located in the main chamber of the ETS. The in-vacuum components and a cut-away view of the ETS are shown in Figure 1.

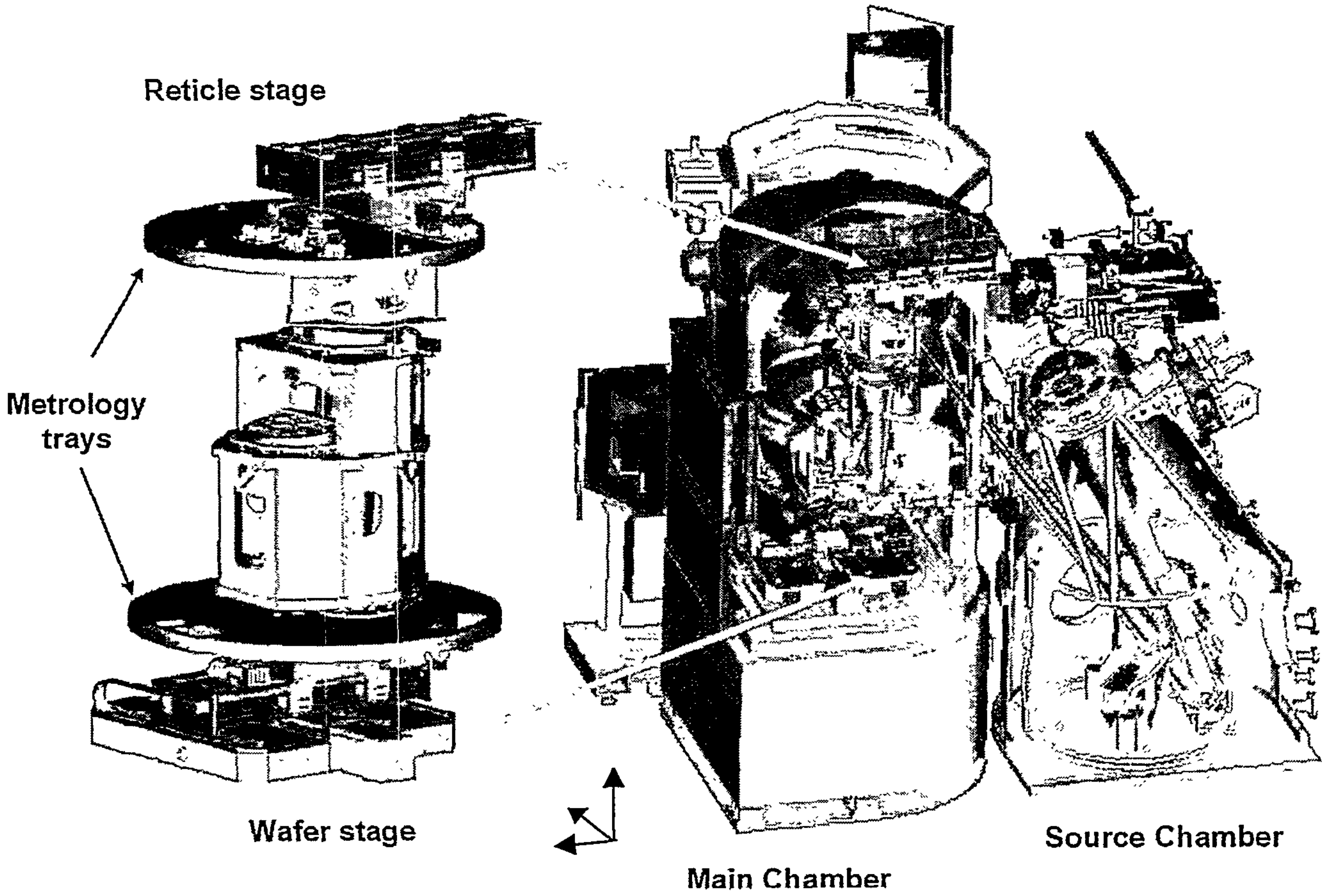

Figure 1: ETS In-vacuum stage components.

The stage supporting structures are the main chamber pedestal and the bridge. The wafer stage is mounted on the pedestal and the reticle stage is mounted to the bridge structure, which also mounts to the pedestal. The pedestal provides a stabilizing mass for the machine and rests on the laboratory floor. The bridge is sufficiently stiff to reduce relative motion between the wafer and reticle stages. The interferometers, beam optics, stage initialization sensors, and focus sensors, are mounted on the wafer and reticle metrology trays. Mirrors are attached to the PO box to provide *X*, *Y*, and θ_Z position referencing for each the wafer and reticle stages. The metrology trays, PO box, and connecting structures are isolated from ground vibration by three isolators that are mounted to the pedestal by the isolator support structure.

3. MAGLEV STAGES

The need to perform EUVL in a vacuum environment places unique requirements on the scanning stages for the ETS. Particle generation must be minimized to eliminate possible contamination of the object reticle, target wafer, and machine optics. A magnetically levitated fine position stage has successfully performed under similar requirements and is in use in the 10X Microstepper[1]. This success combined with the availability of concept maglev scanning stage designs [2,3] led to the inclusion of 1D-long-travel maglev stages for both reticle and wafer positioning.

The wafer stage (Figure 2) consists of the stage base, off-axis coarse stage (the beam of the maglev stage), levitated platen, cable stage, and wafer chuck. The reticle stage (Figure 3) is identical to the wafer stage without the off-axis coarse stage and

is mounted in an inverted position. Each wafer and reticle chuck is kinematically mounted to its respective platen.

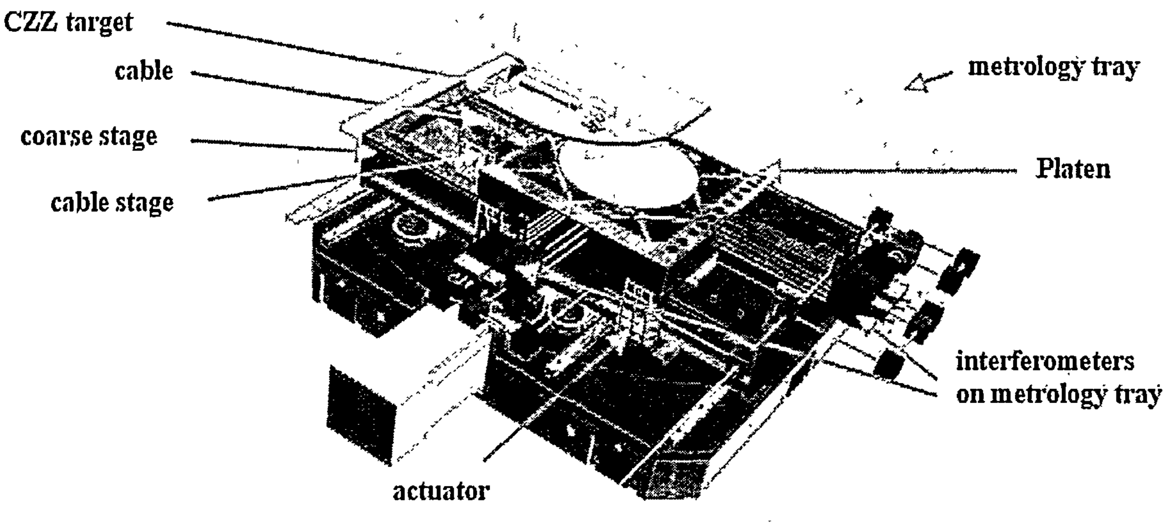

Figure 2: Wafer stage model including interferometry.

The platen is magnetically suspended from the beam and includes the mirrored metrology surfaces. The monolithic platen is machined from Zerodur to reduce mass, help optimize bandwidth, and minimize errors from thermal distortion. The beam travels in the nonscanning axis on linear guides and is driven by a lead screw. The maglev portion of the stage has a travel range of 500 μm in the *X* and *Z* directions, 225 mm in *Y* and 1 milliradian of θ_x, θ_y, θ_z rotation. The stepping axis has a travel range of 370 mm. The six degrees-of-freedom magnetic suspension scanning-axis consists of ten variable-reluctance actuators and a single degree-of-freedom linear motor. The ten variable-reluctance actuators (five bi-polar pairs) control five degrees of freedom and the linear motor controls the long-travel scanning degree of freedom. Gravity offsetting permanent magnets attached to each of the actuator housings support the gravitational load. The control forces applied to the body are completely kinematic due to the actuator configuration.

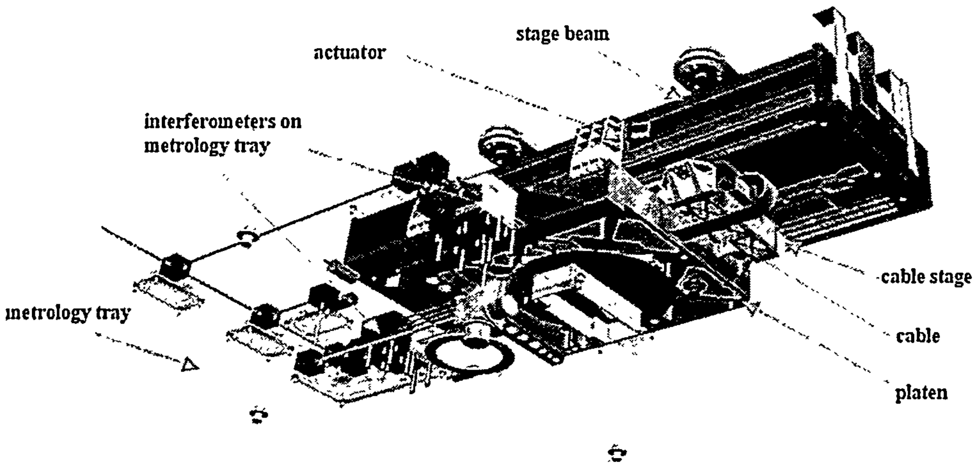

Figure 3: Reticle stage model including interferometry.

Electric current to the variable-reluctance actuator coils is conducted through Kapton flex cables that have well defined single degree-of-freedom rolling paths. Five actuator gap measuring capacitance sensors are located on the stage beam to provide feedback for force linearization. The platen assembly consists of a Zerodur mirror with the active components (actuators, Halbach arranged linear motor magnet array).

Included in the stage design is a cable stage that moves on linear guides and is designed to reduce the disturbance forces imparted on the scanning stage by rolling cables. The cable stage is actuated in the scanning direction by a permanent magnet linear motor that utilizes the maglev linear motor coils. The cable stage follows the maglev stage and is commutated similar to the scanning linear motor. The cable stage position is determined with an optical linear encoder. A capacitance sensor located on the cable stage is used to determine the relative position between the cable stage and the wafer/reticle stage.

The long scanning axis (*Y*) position control is achieved with a Lorentz type planar linear motor. The maglev stage is then transported in the off-axis direction (*X*) by a high-stiffness well-damped linear guide lead screw driven stage. It is not necessary for the lower stage to achieve maximum resolution since the maglev stage has a redundant degree of freedom in this direction which eliminates the positioning dependence on the bearing surface finish. A preloaded leadscrew is used to drive the linear guide stage. The leadscrew is chosen over a linear motor for the lower power dissipation provided by its mechanical advantage. A distinct characteristic of maglev stages is that mechanical complexity is replaced with control complexity. Therefore, the control strategy and hardware implementation is crucial to meeting the performance requirements.

4. CONTROL STRATEGY

The stage controller is implemented in software that runs on several real-time embedded computers. The controller compares the measured positions of the two stages with their desired positions at the controller's sample rate. The controller attempts to drive these errors to zero by a combination of feedback and feedforward strategies. The feedback acts on the measured errors via digital filters to generate corrective forces, while the feedforward cancels disturbing forces before they have a chance to create positioning errors. The control strategy is complicated by cross coupling between axes and the nonlinear nature of the actuators. Position accuracy of the stages during EUV exposure is dependent on many factors. These

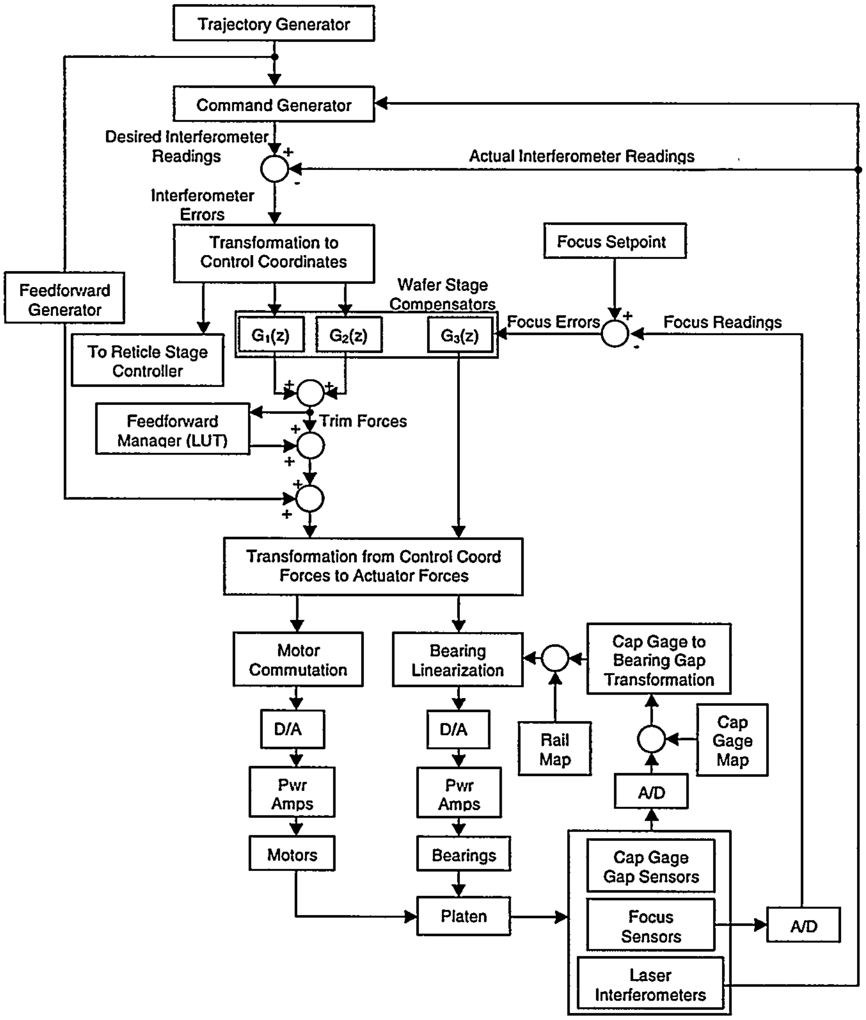

Figure 4: Controller high-level bock diagram (Wafer Stage).

contributing factors include, the stiffness of the overall structures and stages, the accuracy and precision of all feedback sensors and associated electronics, and the control strategy used to manipulate the sensor based information. The control architecture is shown in Figure 4.

The trajectory generator computes a master trajectory for the stages during the scan. This is the desired center position of the exposure window on the wafer at each instant in time. Accelerations derived from the positions are sent to the stage controller through the Feedforward Generator and converted to forces.

The command generator transforms the positions into desired position commands in all six degrees of freedom. Once the desired positions have been calculated, the differences between the actual and desired positions are computed. These are trajectory following errors that the controller attempts to drive to zero. In order to decouple the axes, a linear transformation is used to create modal errors. The modal errors are positioning errors of the stage center of mass in the cardinal directions. The compensators $G_1(z)$, $G_2(z)$, and $G_3(z)$ are digital filters that accept the modal errors as inputs and produce the desired modal forces as outputs. The compensators are implemented as cascaded second-order discrete-time transfer functions. They include phase lead to stabilize the loop, and integrators to decrease the low-frequency errors. There are also notch filters to compensate for structural resonances. The out-of-plane motions (Z, θ_x, and θ_y) have a primary sensor (the focus sensor) and a secondary sensor (either interferometry or a capacitive sensor). The primary sensor measures the location of the surface of the wafer, while the secondary sensor measures the location of the levitated platen. The secondary sensor has other desirable qualities, such as low noise or high bandwidth. Both of these measurements must be combined to achieve the desired performance. The in-plane degrees of freedom (x, y, and θ_z) use only the interferometers for position sensing. For the wafer stage an additional term, estimated image placement error, is introduced to drive the controller.

Repeatable forces used from one scan to the next are stored in a lookup table within the feedforward manager. The sum of the control forces and the feedforward forces result in three forces and three torques that are applied to each stage in the cardinal directions. A linear transformation then determines the force required of the motor and each magnetic actuator to produce the desired modal force.

Once the forces required of the motor and each magnetic actuator have been computed, the currents that will generate these forces are calculated. The force produced by the magnetic actuators is proportional to the square of the current and inversely proportional to the square of the actuator gap. The actuator gap is determined by a position-dependent linear transformation of the capacitive sensor readings. Once the gap is known, the current required to produce the desired force can be computed.

The linear motor is a three-phase motor, and each of the three phases is driven independently. The drive signals are sinusoidal, separated in phase by 60 degrees. Coils are used to drive either the cable stage or the platen depending on Y-position. When the platen is located over a given coil, the platen controller determines the coil current. Likewise, when the cable stage is positioned over the same coil, the cable stage controller commands its current.

5. CONTROL SYSTEM COMPUTER, I/O, AND SOFTWARE

The electronics of the stage control system consist of two instrument bays having VMEbus-based computer, I/O, drive electronics, and custom interface electronics. Hardware and software is a combination of commercially available electronics, custom electronics, and software routines and drivers specifically configured to provide the interfacing of system sensors and actuators, and to execute the control algorithms. The real-time system is comprised of three 64 bit floating point processors, twelve 32 bit floating point digital signal processors (DSPs), 32 analog inputs, 40 analog outputs, 48 digital inputs, 48 digital outputs, eight channels of quadrature decoders, fourteen interferometer channels, three Ethernet connections, and a replicated shared-memory network interface (stage-net). Hardware and software are optimized to maintain a sufficiently high sampling rate to achieve required system bandwidth and reduce signal aliasing. Extensive cable interconnects are required between the in-vacuum stages and the controller.

5.1 Hardware

The hardware system is comprised of an integration of several commercial-off-the-shelf (COTS) and custom-designed boards. The intent of the design is to create a modular system that is easy to reconfigure and expand and to allow the use of legacy software libraries and hardware knowledge. The computer architecture is shown in figure 5.

VMEbus architecture was selected for compatibility with the metrology hardware. All system CPU boards have bus-master capabilities allowing full utilization of the VMEbus. The large board count (30 boards) requires the use of two 21-slot VME backplanes and VMEbus repeater boards to allow communication between the two backplanes.

Digital Signal Processor (DSP) boards use Texas Instrument's TMS320C40 DSPs. Accommodation has been made for system expansion. Extensive use of TMS320C40 communications ports is prevalent in the design. Double precision (64 bit) floating-point processors (PowerPC) were integrated into the system in order to maintain required resolution in floating point for metrology data processing. PCI Mezzanine Cards with onboard Texas Instruments TMS320C44 DSPs installed on the PowerPC boards allow direct communication between the PowerPCs and the DSPs via PCI accesses. The onboard C44 handles routing and floating-point conversion.

System input/output (I/O) boards directly interface to system processors and provide necessary function, resolution, speed, and density of channel count. They include modular I/O Industry Pack (IP) carrier boards with a direct interface to the DSP processor boards. Custom filter boards provide some of the analog inputs and outputs with low pass filtering and voltage offset to match specific analog-to-digital or digital-to-analog IP board requirements. A custom interface chassis houses the filter boards and provides other monitoring and control functions.

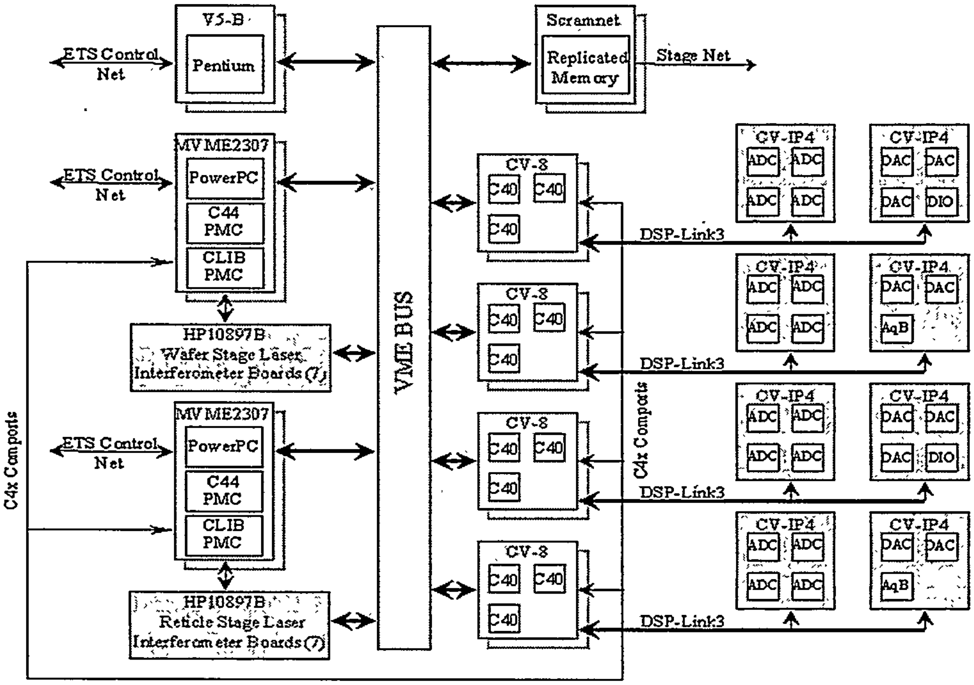

Figure 5: Control system computer configuration.

Laser interferometry interfaces to the system via fourteen Hewlett Packard HP10897 high-resolution laser axis boards. These boards convert interferometry reference and measurement signals from the laser head and measurement receivers to a 36-bit digital position word that is readable over the VMEbus or over the VMEbus P2 user definable pins. A custom laser interface board (CLIB) provides timing signals to strobe all of the I/O, sample the interferometers, and interrupt all of the system processors using a high-accuracy clock. This board allows direct PCI bus-mastering and burst-mode transfer capabilities.

Stage-net allows sharing real-time stage data with other ETS subsystems using a replicated shared-memory network system. Data written into memory in the stage system is automatically updated in the memory residing in other ETS subsystems over a fiber optic link. This allows data synchronization between ETS subsystems with no additional overhead to the local system.

A Pentium-based host computer initializes and monitors the system as well as provides a platform for user interfaces, system development, and data analysis. The host has all of the capabilities of a typical desktop computer running Windows NT 4.0 including hard disk, floppy disk, Ethernet controller, VGA controller, keyboard and mouse, and has a VMEbus master/slave interface.

5.2 Software

Software for the ETS stage control is described in two parts, the real-time software, and the host communication software. The real-time software executes in a deterministic fashion based on a clock generated in hardware. The host communication software executes in the background on a low-priority basis as time allows.

5.2.1 Real-Time Software

The real-time software executes completely in interrupt context. The DSPs and the PowerPCs execute all of the real-time software. The state of the real-time software is determined by commands from the host, completion of tasks, and error conditions that occur in the system. A PowerPC acts as real-time state master and distributes state information at the beginning of an interrupt or servo cycle. All timing for interrupt generation and I/O strobes are performed by signals generated by the CLIB. All input data, and prior cycle output data, are strobed at the beginning of a servo cycle.

Inter-processor communications are critical during execution of the real-time software. All inter-processor communications are via DSP communication ports. The well-defined data flow allows the software executing in each processor to know when, where, and how much data to transmit and when, where, and how much data to expect.

A simplified flow of the real-time software can be described by the following sequence of tasks. Upon interrupt service routine entrance the system state word is distributed. Sensors are sampled and data is collected and distributed. Position transformation calculations are performed. Modal errors are formed. Controller compensation algorithms are executed based on modal error inputs and output modal forces. Modal forces are transformed to actuator forces. Actuators are linearized and are commanded. Performance data is collected. Health checks are performed. The processors return from interrupt context.

Each PowerPC in the system manages its respective stage's position. This includes all calculations and data collection that contains global stage position. The high-precision metrology data is processed on the processors using double-precision floating-point calculations. Double precision floating point is required to maintain sub-nanometer resolution over relatively large distances.

The interferometer data is read into the PowerPC directly from the CLIB. The PowerPCs execute position transformations based on interferometer data and calculate the stage modal errors. A master index is used for long-travel motor commutation switching and all lookup-table indexing based on stage position. Statistical calculations that reflect system performance such as jitter and mean tracking error are performed. The PowerPCs are also responsible for sharing position information over stage-net for use by other ETS subsystems.

The DSPs in the system perform execution of real-time software that does not require double-precision floating-point calculation. They execute the relative position calculations based on capacitive sensors and encoders. Compensator algorithms for each modal axis are performed in the form of infinite-impulse-response (IIR) filters. The IIR implementation allows execution of the compensator filter as well as several notch filters. The DSPs perform commutation of the linear motor, force table lookups, and actuator linearizations.

5.2.2 Host Communication Software

The host communication software executes in the background on a low priority basis. There is no real-time synchronization between processors for host communications. The Pentium computer executes host software that manages communications through a shared memory structure. The shared memory is mapped to the VMEbus as a slave image. Any VMEbus master can access the shared memory window. All of the DSP and PowerPC boards in the system can act as a VMEbus master. Each processor in the system has a dedicated memory block defined within the host communication's shared memory window. A processor block is made up of four regions for continuous position data updating, data writing, commanding the real-time system, and real time data buffering for retrieval by the host.

The host software is based on a networked data server. The data server has the only thread of execution that can access the shared-memory structure. This eliminates the potential for contamination of commands and data. Client applications can attach to the data server through TCP/IP connections. The client applications make requests for data and issue commands to the server.

The host software also interfaces to the ETS Executive. The ETS Executive performs ETS system level monitoring and commanding. The executive interface communicates to the host through two TCP/IP sockets where the host software acts as a network server and the executive acts as a network client.

6. SYSTEM MODELING

A model of the ETS structures, stages, and controls was created to predict performance of the stage subsystem and to serve as a tool in formulating and comparing control algorithms. It incorporates information from the ETS system structural dynamics model and the optical model to yield system performance predictions. The stages are represented in rigid body form. Early model results, along with validation experiments, contributed to ETS design decisions in the areas of stage control, vibration isolation, and overall machine configuration. The MATRIXx simulation tool is used to topographically model the Engineering Test Stand (ETS). MATRIXx is used at a high level to provide block interconnections, numerical integrators, etc. Most of the model exists as user-written C code which feeds into the MATRIXx simulation. The control code is a combination of the code segments used in the actual machine. The top-level representation is shown in Figure 6.

6.1 ETS structural model

Vibration of the machine plays a large role in all aspects of the stage simulation. The floor motion causes the machine to move in inertial space in a rigid-body sense and excites some structural modes of the machine resulting in motion at different points of the machine. Since the capacitive sensor and interferometer mounting points exhibit the machine motion, this information gets fed into the platen control systems. The intentional motion of the platens results in reaction forces that also act on the machine. These reaction forces may also excite structural modes of the machine causing further motion of sensor attachment points. Because of these interactions it is important to use a good representation of the system structural dynamics model to drive the motions at different points of the machine. Lower frequency modes from a high-fidelity full-structural-dynamics model are used to provide this representation. This reduced flexibility model is converted to a state-space format. As the simulation progresses the floor node is moved by applying the appropriate force to the floor node input of the reduced structural model. Floor motions have been measured for several floors and these data are input to the MATRIXx model in the form of time, acceleration, velocity and change of position. Points on the isolated frame used in the model include the mounting points for the interferometers, the mounting points for the reference mirrors, the upper contact points of the three isolators, the sensors used in the focus systems, and the target for the wafer stage vertical capacitive sensor. Each of these points is subjected to rigid-body motions and flexible deformations as specified by the reduced structural model before any computations are performed for stage control system inputs.

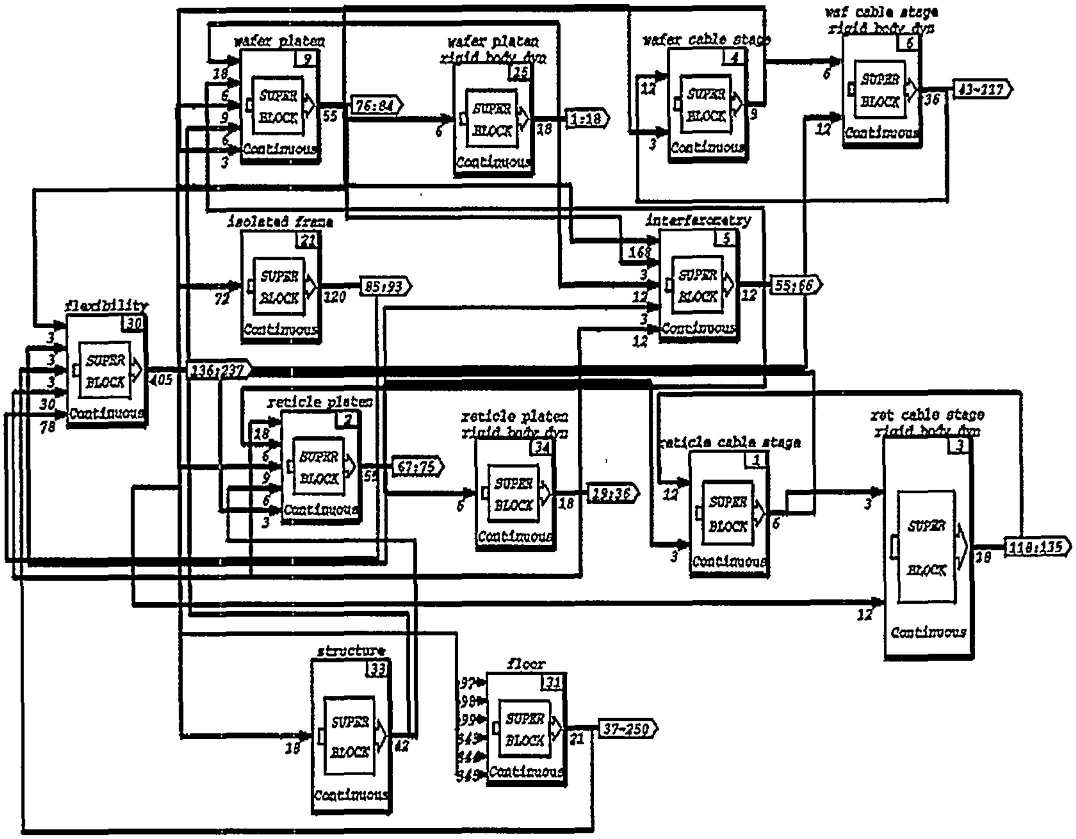

Figure 6: Stage system dynamics model - top level.

The wafer and reticle stages in the stage subsystem model are comprised of the platens and the cable stages. The wafer stage also includes a coarse stage. Both stage's platens are modeled as rigid bodies subject to forces and torques applied by the following sources: gravitational attraction, permanent magnets, cables, and actuators. The cables that run between the platens and their cable stages are modeled as two light rods connected by a torsional spring and damper.

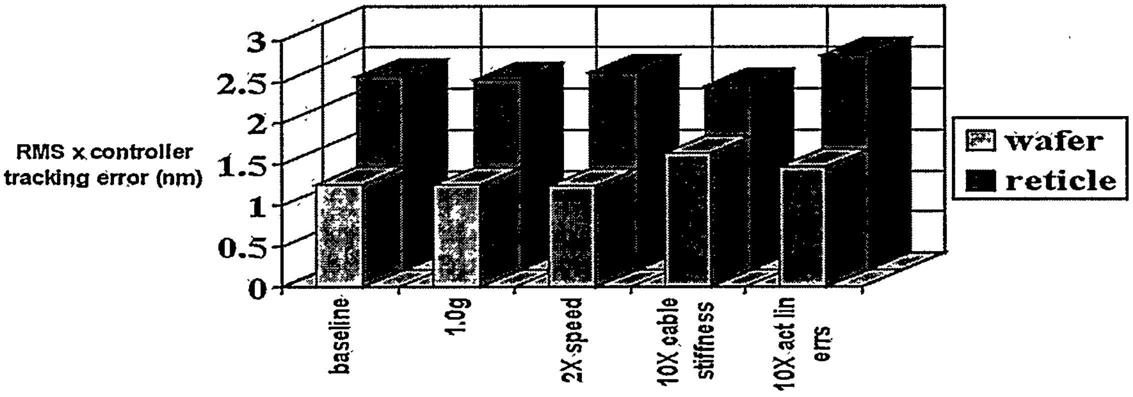

Figure 7: The dynamic model predicts robust ETS performance.

The wafer coarse stage is modeled as a rigid body possessing one degree of freedom (*X* linear motion) with respect to the nearest structural model node. The cable stages are modeled as rigid bodies possessing one degree of freedom (*Y* linear motion) with respect to the stage beam for the reticle stage and with respect to the coarse stage for the wafer stage. Forces acting on the cable stages include friction from guide rails, cable forces, control forces, gravitational attraction and support forces. Inputs to each platen's control code consist of capacitive sensor, interferometer, and linear encoder readings. The model includes seven interferometers for the reticle stage and six for the wafer stage to provide position feedback to the control system.

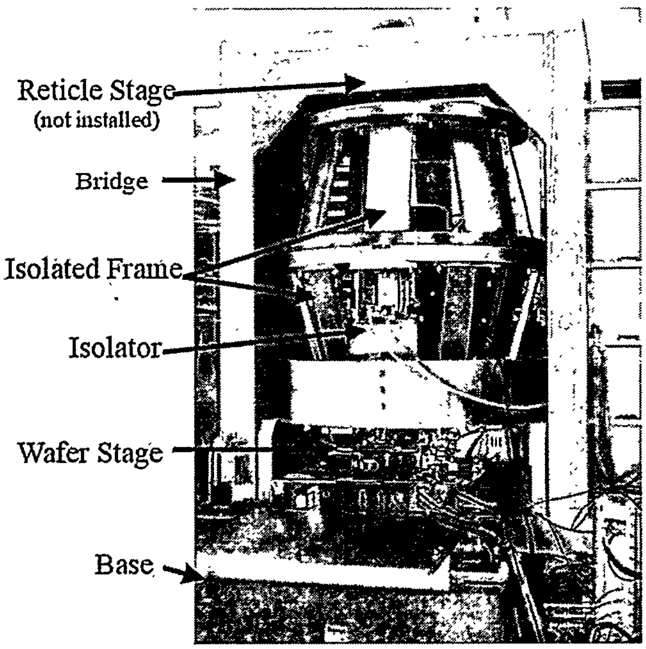

Figure 8: The Stage Development System.

Motion of the PO box as a whole, vibration of the mirrors inside the PO box and platen tracking errors cause the image printed on the wafer to have a placement error in the *X* and *Y* directions. An optical model provides coefficients that tell how much the image will be shifted in *X* and *Y* due to each of these factors. The simulation uses the system geometry at each instant in time to compute the error in each platen's position and orientation. The errors in PO box mirror locations are provided through the reduced structural dynamics model. All these errors are used in conjunction with the optical model coefficients to produce image placement errors in the *X* and *Y* directions.

6.2 Model results

As the modeling evolves to more closely match the actual system configuration, the output reveals the expected performance of the ETS with particular emphasis on the stage positioning system. The results have shown that the system will perform within the ETS specifications. Validation experiments using various test assemblies have supported these findings. A view of predicted stage tracking-error for one axis is shown in Figure 7 for various operating parameters. The data suggests that the ETS and stage subsystem design is robust.

7. PERFORMANCE RESULTS

Stage performance has been evaluated using a prototype wafer stage in a configuration known as the Stage Development System (SDS). The SDS approximates the structural properties of the ETS bridge, isolator support, and isolated frame. It includes the ETS isolator design and approximates the ETS isolated frame with interferometers mounted to metrology trays and a PO box mass mock-up. The SDS is shown in 8 with the wafer stage in place.

7.1 Stage jitter and mean tracking error

Stage mean tracking error and jitter are commonly specified parameters of a scanning stage system. Stage mean tracking error is the difference between the commanded and actual trajectory during a constant velocity scan averaged over a moving 150msec window.

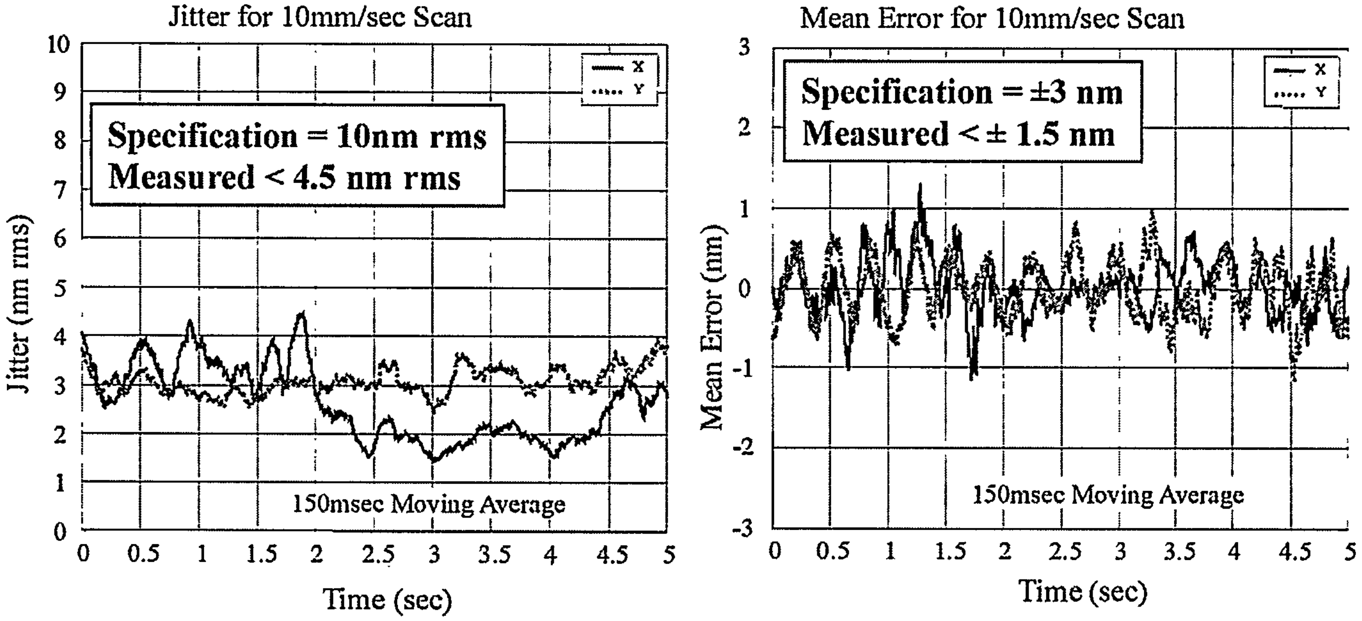

Figure 9: Wafer stage jitter and mean tracking error for 10mm/sec scan.

Jitter is defined as the root-mean-square (RMS) of the difference between the commanded and actual trajectory computed over a 150msec moving window. The ETS requires that the jitter of each stage as referenced to the PO box always be less than 10nm RMS. The mean tracking error must always be less than ±3nm. Performance consistent with these requirements has been demonstrated for the wafer stage and is shown in Figure 9. A controller bandwidth of 50Hz was used for all axes during data collection.

The data indicates that the wafer stage is capable of the required performance. Observed correlation of errors to sources in the environment (floor motion, isolated frame motion) suggests that further performance improvements are possible. The ETS stage subsystem development continues and these ideas and others are being implemented.

8. SUMMARY

The reticle and wafer positioning system for the EUVL ETS is a complex system having some requirements that are unique and some that are similar to current step-and-scan IC lithography tools. Modeling, experimentation, and the development and implementation of demonstrated maglev stage concepts enable the ETS to operate at the performance needed to develop and demonstrate key EUVL technologies. Experimental data obtained from an operating prototype wafer stage demonstrates that it will meet performance requirements.

ACKNOWLEDGEMENTS

1D-long-travel maglev stage design and fabrication is provided to Sandia through a contract with Ultratech Stepper. The 1D-long-travel stage design represents an extension of a Ph.D. thesis by Dr. Mark E. Williams during his tenure at MIT under Dr. David L Trumper. Steve Tracy and Peter Faill also contributed to the design effort.

This work, performed at Sandia National Laboratories, is supported by the Extreme Ultraviolet Limited Liability Company (EUV LLC) and by the U. S. Department of Energy under contract DE-AC04-94AL85000.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

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