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Instrument Design Case Study
Flexure Thermal Sensitivity and Wafer Stepper Baseline Drift

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Abstract

Optical wafer steppers are extremely precise instruments with some very stringent demands placed upon them. They include three-shift production operation, submicron resolution and overlay and high wafer throughput. Registration, a component of overlay, is dependent on the stability of the alignment system and its relationship to the optical axis of the reduction lens. Baseline, the distance between the alignment system and the optical axis, must be stable to for proper operation of the system. Baseline stability in the DSW Wafer Stepper® system has been a issue for a very long time.

A large component of this drift has been traced to a high thermal sensitivity of a flexure in the focus motion actuator. This thermal sensitivity, coupled with the Abbé offset in the alignment microscope and the proximity of the voice coil motor to the flexure, causes a rotation of the optical column. Because of the Abbé offset, this rotation causes a shift in the baseline, which has been previously attributed to other unrelated items.

Remedies for this problem are quite simple once the phenomenon is understood. They include: proper setup of the instrument to minimize the heat generated at the voice coil motor; thermal isolation of the flexure from the voice coil motor with low thermal conductivity materials; redesign of the voice coil motor for higher efficiency; and active control of the motor temperature.

Later designs of the focus motion assembly eliminate the baseline drift problem through the use of high efficiency motors and mechanical design symmetry.

This is a brief study in instrument design to demonstrate how ignoring sound design principles can lead to baffling, almost unanswerable problems.

1. Optical Wafer Steppers

Optical wafer steppers project and align patterns onto photoresist-coated semiconductor wafers to define the processing of each layer during the production of integrated circuits. This process is known as *optical lithography*. Wafer steppers are truly production-oriented precision instruments, used in three shift operation around the world.

All optical wafer steppers utilize three essential systems: the optical system, the alignment system, and a step-and-repeat stage. Reduction optical systems reduce the pattern formed by a chrome-on-glass reticle and project the reduced image onto the wafer. A key element of the optical system of any stepper is resolution. Today's systems can routinely produce submicron images over a 22mm diameter field. The resolution is an important factor since it defines the minimum size of the features of the integrated circuit. Smaller features mean smaller, denser, faster chips.

Resolution alone does not constitue sucessful IC production. Unless the image aligns with the previous layer, viable circuits cannot be produced. This function is performed by the alignment system. By detecting the location of alignment marks placed on the wafer during previous processing, the stepper can then properly place the new images over the underlying levels. This is performed using an alignment microscope mounted on the system. When the alignment microscope is not mounted on the optical axis of the reduction lens, it is known as an off-axis alignment system. The better the alignment system performs, the smaller the chips can be made, and the yield of the chips improves.

The third element of the optical wafer stepper is the X, Y stage system. Since the lens field is much smaller than the diameter of the wafer, the wafer must be moved from site to site. This step-and-repeat cycle is carried out until the wafer is completely exposed. Stages must be highly accurate, and are typically metered by laser interferometers with resolution as high as 0.01μm with a total range of 200mm by 200mm. The speed of the stages is also critical since it is a major contributor to the overall throughput of the stepper.

2. Flexures and Their Use in Steppers

What are flexures? They are elastic mechanical elements that bend or *flex* to provide motion over a small range, and are designed to provide compliance in one direction and high stiffness in others. Several adjustments in the stepper require extremely precise motion over limited ranges. These include the alignment of the reticle, motions to focus the image onto the wafer, and even submicron motions of the stage itself. All of these can be accomplished using flexures.

Flexures have many advantages. They provide frictionless motion and can be designed for linear or rotational motion depending on their configuration. Often, flexures replace complex assemblies with simple strips of metal. They can also be integrally machined into the part itself.

2.1. Flexure For Focus Motions

The flexure used for focus motions on the DSW Wafer Stepper system is a parallel spring flexure. It consists of two spring steel strips that are held parallel by two rigid plates (Fig. 1). Anchoring one of the plates and applying a force to the second produces linear motion.

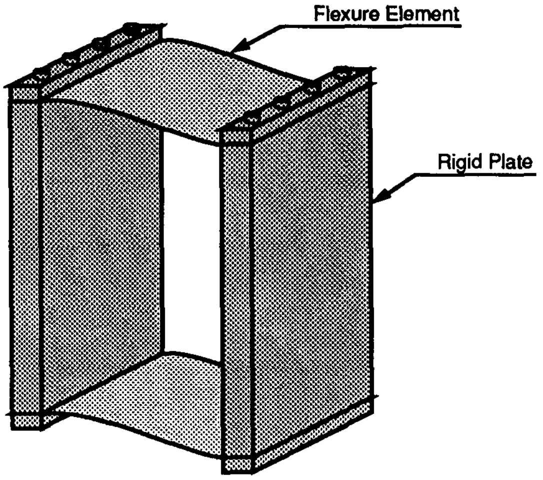

Figure 1. *Parallel spring flexure used for focussing motions in optical wafer stepper. Flexure elements are thin spring steel.*

To move the column (which contains the lens) up and down to focus the image, a parallel spring flexure is placed between the optical column and the bridge (Fig. 2). The linear motion of the column must be straight, that is, not have any tipping, tilting, or twisting motion. Tipping or tilting causes the image plane of the lens to deviate from that of the wafer, thus causing the image to go out of focus at the edges of the field. Twisting motions would cause the image to rotate and therefore not overlay the previous level.

Slight translations in X or Y are allowable in this design, since the mirrors on the column are monitored by the laser interferometer. The interferometer system measures the differential motion between the stage and the column, thus translations of the column due to foreshortening of the flexure arrangement are corrected.

To move the column, a voice coil linear motor is used. The voice coil is an excellent acutator for high precision applications, since it provides a frictionless drive with infinite resolution. In this case, the voice coil drives a lever mechanism that reduces its motion by a factor of ten. To accomodate the weight of the column (so that the motor does not carry all of the weight), a counterbalance spring is used. This spring has a low spring rate so it does not load the motor excessively.

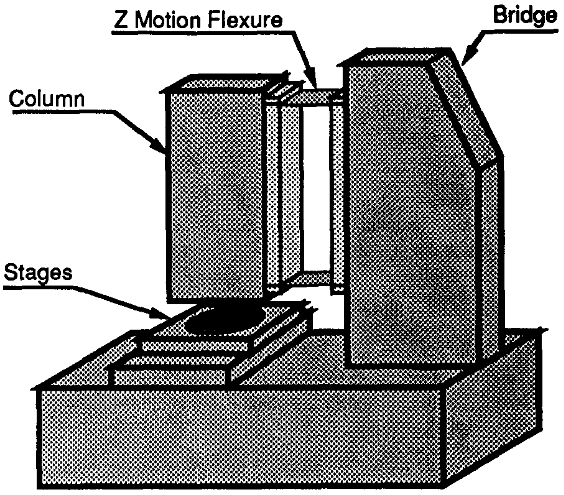

Figure 2. *Parallel spring flexure mounted between column and bridge of the wafer stepper.*

3. Stepper Alignment Systems

In an off-axis alignment system, the microscope and alignment system are mounted away from the optical axis of the reduction lens. For proper system operation, the distance between the alignment microscope and the optical axis must be known precisely. Test procedures determine this distance and record it into the stepper's control system. Once the alignment marks have been located by the alignment system, this distance is subtracted from the current stage position to determine the correct stage position to expose the sites on the wafer.

Two marks on the wafer are used to align the wafer in X, Y and theta. Two microscope objectives are used, one for each mark. The right objective is used to align X and Y, and the left to align theta. The distance between the optical centerline of the reduction lens and the X, Y alignment microscope objective is the alignment baseline. The baseline must remain stable during the exposure of a batch of wafers, since drift in the baseline causes misalignment on the wafers, requiring wafers to be reworked and/or lowering the final yield of devices.

3.1. Baseline Drift

Baseline drift was discovered on batches of wafers of 100 or more, when a customer was attempting to attain better performance from the system than was specified. After tracking several lots, the drift appeared to be consistent on a particular machine, but variable from machine to machine. At worst, the drift was 0.35µm. One factor was common to all machines: the drift was more prevalent in the X axis than the Y axis and was accompanied by microscope rotation. The drift was in the negative X direction and demonstrated a classic exponential response curve. Microscope rotation causes the entire array of exposures to be rotated on the wafer.

There have been several theories about baseline drift. Most were centered around the voice coil motor used to position the X fine stage. The stage steps more in X than Y and therefore the X motor's temperature is higher as a result. The thermal time constant of the X voice coil motor was measured and found to be about 20 minutes, close to the time constant of the baseline drift. Measurement of the stage expansion as a function of the coil temperature was also measured, but found to have a much longer time constant (approximately 7 hours). Speculation that heat from the voice coil was causing a scale change in the X axis interferometer was also discussed, although measurements did not support this theory.

Ultimately, the X voice coil motor induced drift theories were false since the alignment process aligns the wafer with the system at each wafer, correcting for any mechanical drift in the stage. The alignment system compensates for this at each wafer. This concluded that the source of the baseline drift was definitely in the alignment system.

4. The Interaction Between Thermal Sensitivity of Flexures and Baseline Drift

Close examination of the Z motion assembly shows an important clue to the cause of the drift. This reveals that the voice coil motor is located very close to one edge of the bottom flexure. As the column moves to focus the image, the temperature of this voice coil increases. Heat from this motor is transferred to the edge of the bottom flexure. This particular flexure element is made of thin spring steel sheet. Because of its geometry, the heat transfer across the element is very poor and a large thermal gradient is generated.

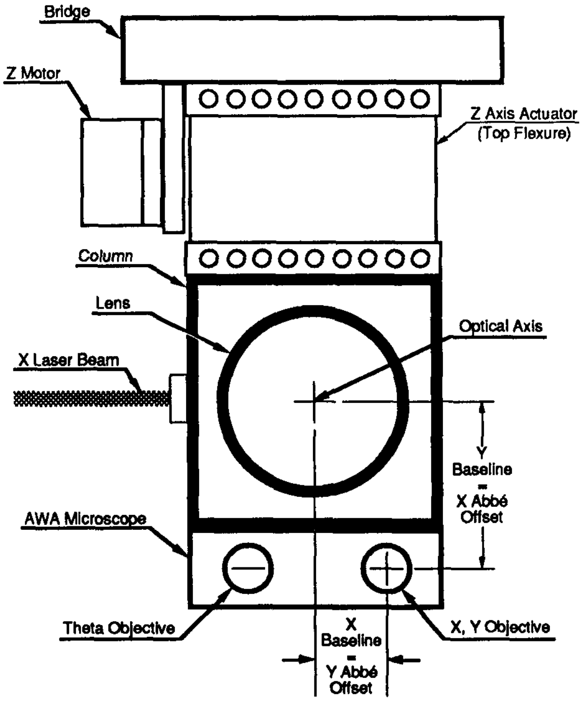

Figure 3. *Top view of optical column and bridge assembly. Note that the AWA (Automatic Wafer Alignment) microscope is mounted to the front of the column, causing a long baseline in the system. This baseline represents an Abbé offset.*

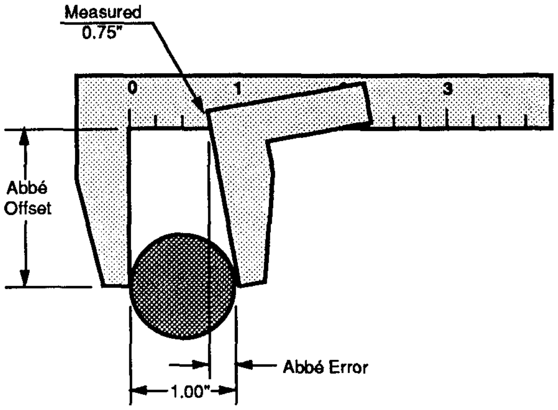

Figure 4. *Example of Abbé error found in a caliper with a loose jaw. Because the jaw rotates slightly and the object being measured is far from the scale of the caliper, a measurement error results.*

This thermal gradient causes a differential expansion across the flexure. This in turn results in an angle between the front and rear plates of the Z motion actuator, which induces a rotation in the optical column.

How does this rotation cause the baseline of the system to drift? The key to this question is in the way the alignment microscope is mounted to the column. Since the microscope is mounted to the front of the optical column, it is not on the optical axis of the machine. Because the microscope measures at the point away from the optical axis of the reduction lens (where the measurement *should* take place), it has a great deal of Abbé offset (Fig. 3).

4.1 Abbé Errors

Abbé offset is a common measurement problem. Often it is impossible to move the scale or measurement tool as close to the object as necessary. Any angle introduced in the 'parallels' between the scale and the object to be measured results in an error. This Abbé error is a function of the length of the parallels and the angle between them. A simple example is a set of vernier calipers with a loose jaw (Fig. 4). The loose jaw (one of the two parallels) causes an inaccuracy in the reading that is proportional to the angle of the jaw times the length between the object and the scale. The problem arises because the loose jaw rotates slightly, creates a small angle and because there is some distance between the object and the caliper's scale.

The Abbé offset in the alignment microscope combined with column rotation caused by heating of the lower flexure results in a drift of the alignment microscope position relative to the optical axis. This represents a drift in the baseline.

The rotational sensitivity of the column as a function of a the thermal gradient across the flexure is easy to calculate. A simple model shows that when one edge of the flexure is a different temperature than the other, the gap between the front and rear plates attached to the flexure will be different at the two edges. The plates will therefore no longer be parallel and some small angle will exist between them. This is easily calculated. It is

$$\angle r = \frac{\Delta w}{l} \tag{1}$$

where $\angle r$ = angle between the plates, Δw = difference in length between the free edges of the flexure and l = length of the flexure (Fig. 5).

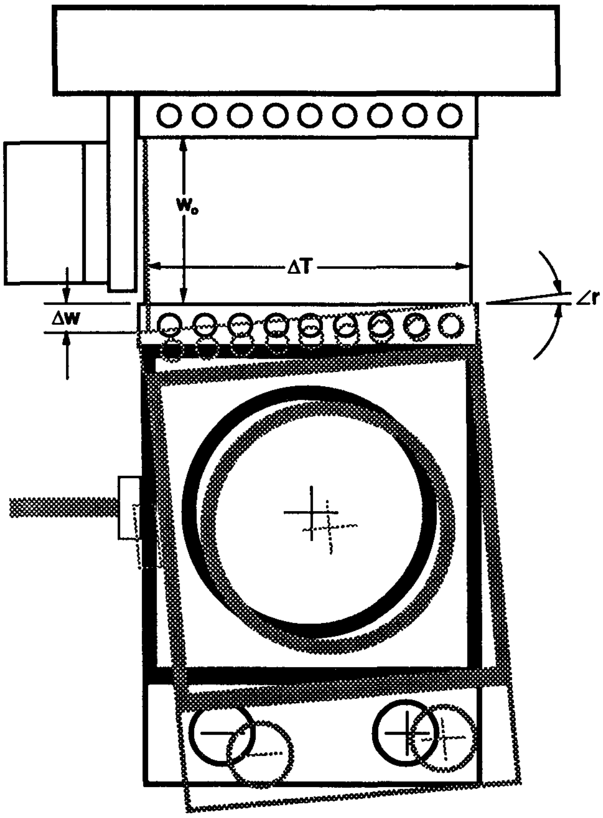

Figure 5. *Flexure thermal distortion leading to rotation and translation of the optical column.*

The change in length of the flexure as a function of temperature difference is

$$\Delta w = w_o \Delta T(CTE_{Fe}) \tag{2}$$

where w_o = nominal width of the flexure, ΔT = temperature difference between the free edges of the flexure and CTE_{Fe} = coefficient of thermal expansion of steel. Substituting Eq. (2) into Eq.(1) yields

$$\angle r = \frac{w_o \Delta T(CTE_{Fe})}{l} \tag{3}$$

and the thermal sensitivity is therefore

$$\frac{\angle r}{\Delta T} = \frac{w_o(CTE_{Fe})}{l}. \tag{4}$$

To determine the magnitude of this sensitivity, the values found on the system are substituted into Eq. 4

$$\frac{\angle r}{\Delta T} = \frac{3.25"(11.7 \times 10^{-6}/°C)}{6.375"} \tag{5}$$

$$= 5.97\ \mu rad/°C = 1.2 arcsec/°C. \tag{6}$$

To determine the effect this thermal sensitivity has on the baseline stability, this value is multiplied by the Abbé offset. Since the Abbé offset for x is the y baseline (and vice versa), the overall thermal sensitivity for the x baseline is

$$\frac{\Delta x_{baseline}}{\Delta T} = \frac{\angle r}{\Delta T} y_{baseline} \tag{7}$$

$$= 5.97 \mu rad/°C \times 111mm \tag{8}$$

$$= 0.66 \mu m/°C.$$

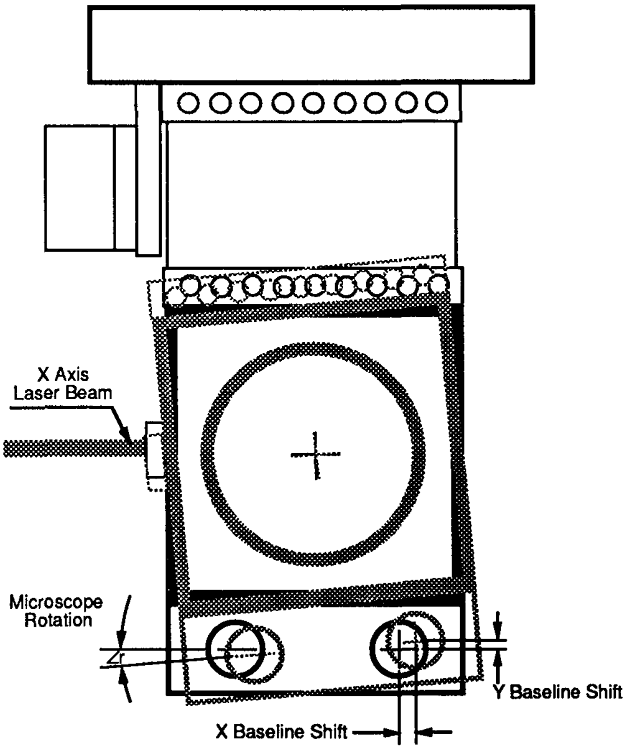

Figure 6. Baseline shift and microscope rotation caused by column rotation. The actual shift occurs from a rotation around the optical axis. This is because the X and Y translations are compensated by the differential laser interferometer system. Y laser beam hidden by flexure assembly.

The *y* baseline sensitivity is less because the Abbé offset is less. The sensitivity of 0.66µm/°C is very high since the maximum registration error is 0.35µm. This means that a change of 0.5°C across the flexure would cause the system to move out of specification.

This drift is caused by heat from the voice coil motor differentially expanding the flexure. This rotates the column causing the microscope to drift due to of the Abbé offset. This drift is strictly a function of the temperature difference between the free edges of the flexure, and therefore exhibits a classic exponential response (being a function of the time to heat the coil and the time to transfer that heat to the flexure).

The column appears to rotate around the optical axis (Fig. 6) because the X, Y interferometer system measures at the optical axis (i.e. it has zero Abbé offset). Translation that occurs is therefore compensated.

5. Resolution of the Problem

Once the problem is understood, the solutions are fairly simple. The first solution attempted was to change some of the materials from aluminum to Delrin®. Delrin has approximately 1/1000th the thermal conductivity of aluminum (0.13 Btu·ft/hr·ft^2·°F as compared to 110). This solution worked well, but could not be installed in the field.

A second solution is to actively control the temperature of the motor. This can be done by adding a heater to the motor and sensing the motor temperature. By holding the temperature of the motor at a fixed temperature above ambient, with either the coil or the heater providing the necessary power to maintain the temperature, the flexure attains a fixed temperature differential after some warmup time. This solution works quite well, except for the complexity and expense of heaters, sensors and controllers added to the system.

Another solution is to make the system more symmetrical. When the motor is placed near the center of the flexure instead of the edge, motor heat does not cause the rotation of the assembly. This solution has been used on new instruments, but again could not be installed in the field.

The last solution is to design a more efficient voice coil motor. This was accomplished using neodenium iron magnets, which have extremely high energy products, and a redesigned coil. By reducing the coil resistance from approximately 12 ohms to less than 2 ohms while maintaining the same force constant (lbs/amp), the power dissipated is reduced by a factor of six. This solution is the best since it inexpensive and easy to install in the field.

6. Conclusions

There are several lessons in practical machine design that can be learned from this experience. The first is to understand the Abbé principle. This does not mean that all systems must be designed with zero Abbé offset, but one must understand the errors that can be introduced when this is ignored. It *is* possible to design a microscope system with zero Abbé offset that does not pass through the lens.

A second lesson is symmetry. The voice coil placed to one side of the flexure assembly caused problems because it heated the flexure unevenly. The problem was not the heat, but its uneven distribution or thermal gradient.

Another lesson is to watch for high thermal sensitivities in the design. Although it was not obvious in this design, it was the high thermal sensitivity of the flexure coupled with the Abbé offset of the alignment microscope that caused the baseline drift.

7. Acknowledgements

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