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Design and control of a piezoelectric driven reticle assist device for prevention of reticle slip in lithography systems

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ABSTRACT

This paper presents a device for managing the inertial loads on photoreticles of lithography scanners. At high scan accelerations, the reticle inertial load can approach the clamp force limit. As a result, nanometer-level presliding slip can occur. Reticle slip is one limitation on increasing the throughput of the lithography scanners. In this paper, we present a reticle assist device which can eliminate reticle slip by compensating better than 95% of the inertial loads when tested in a bench-top tester. The reticle assist device consists of a coarse approach mechanism, for accommodating reticle load/unload, and a piezoelectric stack for fine actuation. The device utilizes a sensorless control system design. The control system uses a self-sensing contact detection method, which is inspired by self-sensing scanning probe microscopy, to find the reticle edge. It also uses a charge amplifier with a novel hybrid hysteresis compensation technique to linearly control the piezoelectric actuator extension, without the need for closed-loop position control. When tested with a replicated force profile with 60 N peak force and 6400 N/s force rate, the assist device compensated better than 95% of the inertial load.

1. Introduction

Lithography scanners print integrated circuits. They expose a die on a wafer by sweeping a slit of light passing through a photoreticle [1]. A simplified schematic diagram of a lithography scanner is shown in Fig. 1. The scanner's reticle and wafer positioning stages move the reticle and the wafer relative to the fixed optical column. In this way, a mirror image of the pattern on the photo reticle is exposed onto a die on the wafer. The optics have a demagnification of four times which means that the area of a die is 16 times smaller than the reticle's. This also means that the reticle stage needs to accelerate and move four times faster than the wafer stage. As the scan rate is increased in an effort to increase the throughput, the reticle's inertial force can become large enough to result in nanometer-level pre-sliding slip or large sliding slip of the reticle relative to the reticle stage. Reticle slip is thus one of the limitations preventing an increase in the scanners' throughput. We have designed a reticle assist device which can prevent reticle slip by exerting a feed-forward force on the reticle's edge to cancel the inertial load. While the assist device can eliminate one key limitation on increasing the throughput, other limitations, such as bubble formation in the case of immersion lithography and limited force capacity in general, may still exist. This paper focuses on the design, control, and experimental demonstration of the assist device in a bench-top test setup.

This section provides more detail on the reticle slip problem, the application requirements, and the prior art. Section 2 shows the mechatronic design of the assist device. Section 3 describes the control system design. Section 4 presents experimental results showing successful reticle slip prevention in a bench-top test setup.

1.1. Reticle slip problem and application requirements

To avoid deforming the reticle, the reticle stage holds the reticle using a vacuum clamp. Friction joints have hysteretic deformation versus force characteristics which result in pre-sliding slip as the interface is loaded. Pre-sliding slip occurs when a portion of the surface asperities slip while the remaining asperities stay connected. The hysteresis and the pre-sliding slip become more significant as the loading approaches the joint's static friction limit. The reticle size and shape are set by industry standards. Therefore, the available vacuum clamp area is limited. Given the restriction on the allowable materials, the coefficient of friction at the clamp's interface cannot be increased. As a result, a limit is set on the clamp's maximum force carrying capacity. The reticle inertial force for the next generation scanners can approach or even exceed this limit. Consequently, reticle slip can be a significant error source for the next generation scanners.

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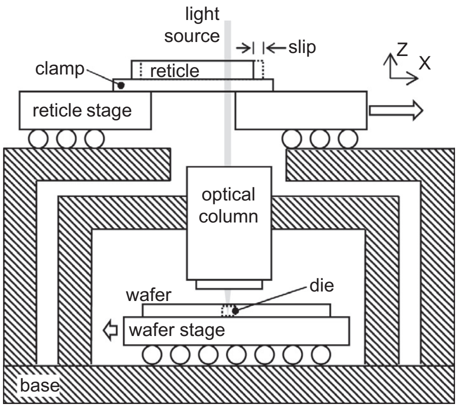

Fig. 1. Simplified schematic diagram of a lithography scanner.

For a reticle mass of approximately 0.320 kg, a peak acceleration of 200 m/s^2 results in a peak inertial load of 64 N. To prevent reticle slip, the assist device must create a force on the reticle to cancel the inertial load and reduce the load carried by the reticle clamp to well below its limit. Pre-sliding slip is considered acceptable if the load carried by the clamp is limited to less than 30 N. Reducing the clamp force even further can have benefits such as further reduction of pre-sliding slip and settling time; however, these returns are subject to the law of diminishing returns.

The following is a list of main application requirements, which have guided the design of the initial assist device prototype. This is not intended as a final requirement list and has only been used as a guideline for our research and development.

1. *Force compensation:*
   The device must counteract better than 60% of the reticle's inertial force for maximum inertial load of 64 N and load rate of 6400 N/s.
2. *Dynamics:*
   The dynamics and the mass of the assist device affect the dynamic of the scanner. The mass of the assist device must be limited to 0.15 kg per side and its vibration modes must be above 1 kHz.
3. *Limited disturbance:*
   The forced displacement or deformation of the reticle outside of the acceleration intervals, when exposure is occurring, must be limited to 1 nm within the pattern or mask area. Also, the stiffness of the cables and lines connecting to the assist device can disturb the positioning stage and must be limited.
4. *Reticle requirements:*
   The standard reticle length tolerance of ±0.4 mm must be tolerated by the assist device. The stresses created in the reticle must be limited by avoiding reticle-device impacts and proper tip design.
5. *Lithography requirements:*
   The device cannot block the light cone. Contamination by particle generation or leakage is not allowed.
6. *Lifetime and reliability:*
   Lithography scanners are designed with high reliability. Operation for at least 7 years with minimum down time is expected. During the assist device's life time, 1 million reticle exchanges and 500 million pushing cycles can be expected.

1.2. Prior art reticle assist devices

The prior art solutions can be categorized into two groups according to their general approach toward solving the reticle slip problem: clamp mechanism modification and inertial force canceling devices.

1.2.1. Clamp mechanism modification

The reticle slip problem can occur when the reticle inertial load exceeds the clamping force limit. As a result, improving the clamping mechanism is one potential way to solve the problem. Shibazaki uses a mechanical clamping mechanism, which can increase the normal force available for clamping the reticle [2,3]. The reticle is clamped between a rigid support and the clamping end, which is made flexible to distribute the clamping forces. Baggen et al. propose using actuators to exert opposing clamping forces on the reticle only during the acceleration intervals and not through the constant speed scan intervals when exposure occurs [4]. In this way, the reticle deformation resulting from the additional clamping forces is not present during the exposure interval and thus will not distort the printed layers. Zordan suggests that a clamping structure which is more compliant to the shape of the reticle can have a higher slip force limit even without increasing the clamping forces [5]. Naaijkens developed a side wall kinematic clamping method, which replaces frictional clamping forces with normal forces on the side wall [6]. Naaijkens's clamp design uses struts with aerostatic spherical bearings to accommodate the reticle side wall squareness and skewness.

1.2.2. Inertial force canceling devices

Another way to prevent reticle slip is to use a reticle assist device to exert an external force, which can fully or partially cancel the inertial load. Iwamoto describes a reticle assist device which generates the compensating forces using the inertia of two masses and a lever mechanism [7]. Jacobs et al. propose using linear actuators with a lever mechanism to exert a force on the reticle [8]. Baggen et al. suggest that clamping actuators, which will be oriented in the scan direction, can also be used to exert a net force on the reticle to cancel the inertial load [4]. Del Puerto and Zordan propose a linear reticle assist device, which uses linear motors to exert pushing forces on the reticle [9]. Amin-Shahidi designed a solid-state reticle assist device consisting of a coarse approach mechanism for adjusting to the reticle length tolerance and a fine approach mechanism for exerting the pushing force to cancel the inertial load [10]. The assist device, which is discussed in this paper, is designed following this last approach.

2. Mechatronic design

The assist device is designed for exerting a force on the reticle's edge to cancel the inertial load and prevent reticle slip. This section describes the design of the assist device as well as the experimental setup used for evaluating its effectiveness. Fig. 2 shows the experimental setup. Fig. 3 shows an schematic diagram of the experimental setup including the assist device and the reticle assembly. The reticle assembly has been provided to us by ASML[1] and consists of the reticle, reticle clamp, and the force actuator. The reticle is fixed to the stationary frame using the reticle clamp. A linear Lorentz force actuator, with its coils attached to both sides of the reticle, is used to create a force (F_I) on the reticle's center of mass in the X-direction (scan direction). The force (F_I) is used to replicate the reticle inertial load and to enable testing of the assist device in a stationary bench-top setup.

A CAD model of the assist device is shown in Fig. 4. The device consists of a coarse stage and a fine stage. The coarse stage is used to account for the reticle length tolerance. It moves the fine stage

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[1] ASML is a provider of lithography systems for the semiconductor industry (www.asml.com).