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Modelling and Compensation of Thermally Induced Positioning Errors in a High Precision Positioning Application ⋆

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Abstract: Thermal scanning probe lithography (t-SPL) is a promising technology to create patterns at the nanometre scale. So far, a commercially available t-SPL tool only exists for small, centimetre scale work pieces typically used in the university research environment. Scaling this technology to work with industry standard wafers requires much larger mechanical positioning units. These are subject to thermally induced deformations and consequently positioning errors. This work suggests a model based compensation of a mechanical positioning unit in combination with a direct position measurement enabled by the t-SPL patterning tool. Based on a linear model of the positioning unit, a Kalman based filter is designed, to estimate thermal errors during the patterning process and use position measurements between patterning phases for re-calibration. The presented filter does not require additional measurement equipment for the compensation. An application of the presented algorithm on an experimental set-up shows a significant reduction of thermally induced position errors.

Keywords: State-space model, Position estimation, Position error, Kalman filter, Active compensation

1. INTRODUCTION

High precision manufacturing systems capable of producing features in the nanometre scale are a key success factor in semiconductor industry. Scanning probe lithography (SPL) is one of many technologies to apply nano-scale patterns on surfaces. As mentioned by Garcia et al. (2014), SPL uses a sharp probe to modify the surface of the work-piece. In thermal SPL (t-SPL), heat is applied to this probe during the patterning process of temperature sensitive materials. The cooled down probe can be used like an atomic force microscope to measure the topology of the surface. Hence, this technology allows serial writing and reading on a work-piece with the same tool. To access the whole surface of industry sized wafers, stroke lengths of up to 0.6 m are required. As shown by Paul et al. (2015), this stroke length can be achieved by combining a t-SPL patterning unit with a mechanical positioning unit. However, this combination of two systems raises new challenges due to thermally induced deformation of the positioning unit. The goal is now to account for this deformations and compensate their negative influence to the patterning process. Using the reading capability of t-SPL in combination with the surface roughness of the work-piece, Paul et al. (2012) identify position offsets and align different patterns. This process is termed stitching. It requires a minimum imaged area to compute position offsets, thus it can only be invoked intermittently. This is not possible during the writing process, when the probe is heated. Hence a new approach to compensate thermal deformations during the writing process is required.

Thermal effects and thermally induced tool center point (TCP) errors are well known issues in machine tool industry (Mayr et al., 2012). There are different approaches to compensate thermal effects on machine tools. Goal of model based compensation is to predict the TCP error based on available inputs. Especially in the design phase of new machine tools, the finite element method (FEM) is used (Gomez-Acedo et al., 2012; Franke et al., 2010). As stated by Mayr (2009), FEM based aproaches are often not suitable for real-time applications due to the computational effort. Hence, reduced models – i.e. rigid body models (Okafor and Ertekin, 2000) – or phenomenological approaches – as by Gebhardt et al. (2013) – are used. Efforts in the direction of self learning models are made as well. Ramesh et al. (2003) for example use a hybrid Bayesian network, where as Yang and Ni (2005) apply recursive dynamic modelling. A new approach is presented by Gomez-Acedo et al. (2013). The authors use a Kalman filter to estimate TCP errors and the machine temperature distribution based on the current operational point of the machine. This state of the art overview shows the diversity and successful applications of model based compensation of thermally induced TCP errors on machine tool. The

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question is, whether those can be applied to compensate thermal errors on a positioning unit for a t-SPL tool.

This work combines a model based estimation of thermal effects with the position measurement capabilities of scanning probes, by means of compensation of thermally induced TCP errors. The approach builds on the available hardware, and does thus not require additional metrology to compensate thermally induced TCP errors. In the first part, the test-system itself is introduced, while the second part focuses on the thermal modelling of this particular system. In the third part, a filter is designed for the intended compensation task.

2. TEST SYSTEM

2.1 System configuration and measurement set-up

The test bench used in this work is visualized in figure 1. It consists of a two axis linear position system of the type *Saphir* produced by *Schneeberger Linearsysteme AG* and a cross grid system of *Heidenhain*. In this testing set-up, the cross grid system takes the position of the lithographic patterning tool. Additional measurement systems are installed to obtain the ambient conditions, inputs to the system, thermal states (temperature distribution) and resulting TCP errors:

- The currents of the three phases of both linear motors are extracted directly from the analogue power amplifier using the RS232 interface. (Remark: Only two phases of each motor are directly measured, while the third phase results from the star serial circuit.)
- x- and y-components of the stage position as seen by the position controller are obtained using the command line interface of the device (ACS, 2008).
- The actual TCP position is observed by the above mentioned cross grid system. The cross grid is mounted on the moving platform of the stage, while the scanning head is fixed on an aluminium bridge connected to the granite table.
- Temperatures at distinct positions on the stage (structural elements and linear motors), as well as on surrounding elements (ambient air, granite table and aluminium bridge) are measured by a total of 16 thermo-elements connected to an *NI-9214* DAC-system.
- Using a *gSKIN-XI* heat flux sensor (greenTEG AG, 2016), the convective heat flux is directly measured on the surface of the structural elements of the x-axis.

All discussed sensor readings are recorded and processed by a specially designed *Labview* program.

2.2 Definitions

Goal of the positioning is to align the TCP with the desired contact point S on the work-piece. Deviations between the two points are in this context referred to as TCP errors. This leads to the following definitions:

$\underline{r}_{TCP}$	Position vector of the TCP
$\underline{r}_S$	Position vector of the desired contact point between tool and work-piece
$\delta\underline{r}_S$	Resulting TCP error $\delta\underline{r}_S := \underline{r}_{TCP} - \underline{r}_S$

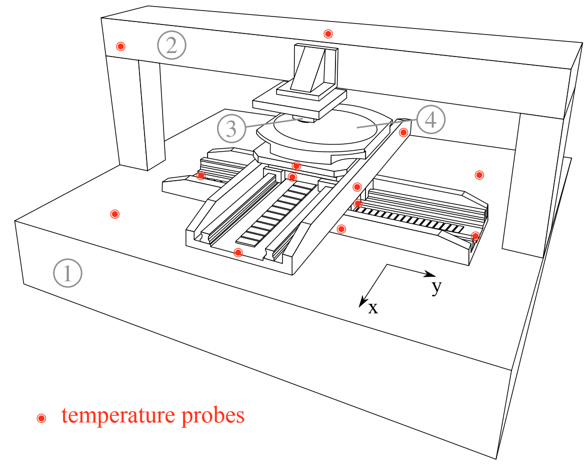

Fig. 1. Measurement set-up built on a granite table ①. The aluminium bridge ② is holding the scanning head / TCP ③ of the grid plate ④.

2.3 Performance evaluation

Repeatability In positioning applications, the repeatability as defined in the standard ISO 230-2 is one of the key performance indicators. The characteristic step size of the indented process of this positioning application is 200 µm. Following the measurement procedure in ISO 230-2, the two-sided repeatability for the two axes for the mentioned step size is obtained:

$$R_x = 100 \text{ nm} \quad \text{and} \quad R_y = 137 \text{ nm} \tag{1}$$

Environmental influences Using the readings of the heat-flux sensor in combination with the temperature measurements of structure surface and ambient air, a heat transfer coefficient (α) can be estimated. The uncertainty is mainly determined by the uncertainty of the temperature readings (0.15 K). The estimated α for convectional heat transfer on the test bench is given as

$$\alpha \approx 10 \pm 1.5 \text{ W/K/m}^2. \tag{2}$$

Thermally induced deviations To quantify and analyse the thermally induced TCP errors to be expected during patterning, a typical process is simulated. Hereby, a field of 2×2 mm is covered in steps of 200 µm. While the sign feed is performed by the lightweight x-axis, the linefeed is realized by the y-axis. Each position is held during 120 seconds, while the TCP position is measured on the cross grid. Figure 2 shows the analysis of this measurement. Each thermally induced deviation at the TCP is characterized by its total length and average direction relative to the x-axis. About 56 % of the measured TCP errors show a total length equal or bigger than 10 nm, while the direction of the deviations are almost uniformly distributed. The standard deviation of the TCP error over all measurement points is 9.8 nm. Furthermore, no correlation between the stage position and the measured thermal deviations can be found.

3. SYSTEM MODELLING

The modelling of the positioning stage is divided into three steps: Characterization of the internal heat sources,