High Precision Measurement of Length and 2D-Coordinates at the PTB

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Abstract:

We report on recent developments and current state of art of PTB measurement capabilities on one- and two-dimensional material measures of length like e.g. line scales or photomasks as well as length measuring systems like e.g. laser interferometers or linear encoder systems. The talk will describe the instrumentation developed and used at the PTB to perform high precision length measurements with uncertainties in the nanometer range. For instance the newly developed nanometer comparator is designed to obtain measurement uncertainties of about 5 nm on 1D-objects with dimensions up to 600 mm. Different 1D and 2D-comparators with variations of detection systems, environment and type of displacement measurement are used for systematic investigations in length metrology as well as for calibration services.

1. Introduction

Traditionally, high precision length calibrations were focused primarily on measurements of prototypes with 1 m length. Most of the sophisticated, high precision line scale comparators which were developed at the different national metrology institues (NMI´s) in the past were optimized for the measurement length of 1 m. Several international line scale comparisons on 1 m scales of steel and invar with scribed lines on it were conducted [1, 2]. The degree of coincidence of the length measurement results found .e.g. in [1] was reasonably good. For the measurement of an interval L, the standard deviation s of the result from any laboratory with respect to the mean of all 12 laboratories was found to be: $s = 0{,}03\ \mu\text{m} + 0{,}08 \cdot 10^{-6} \cdot L$.

Today, however, the smallest measurement uncertainties in the nanometer range are required over measurement lengths which in general are well below one meter. Very demanding requirements for high precision length and coordinate measurement are formulated by several high-tech industry branches: Wafer to reticle alignment or overlay issues in semiconductor production, CD/DVD disc mastering process, manufacturing of length scale measuring systems, x-y-stage metrology, fast position servo control systems, ultra precision machining. Most of these applications are critical for lengths up to 300 mm, some require length measurement capabilities of up to 600 mm. However, measurements over one meter length are rarely needed with uncertainties of a few nanometer.

All of the comparators applied to perform traceable length calibrations on material measures of length basically consist of two indispensable components: a line position detection unit or reading head and a unit to provide and measure the relative displacement between measurement object and the detection unit or reading head. The majority of existing line scale comparators do operate in air and use different types of optical microscopes for line position sensing. For displacement measurement of either the moving line scale on a carriage or a moving microscope, laser interferometry is applied. In order to determine the actual wavelength of laser radiation in the measurement path of the interferometer, the refractive index of air has to be known precisely. For this, either a direct measuring refractometer or an indirect parametric method can be used. For the latter one, critical parameters of air, namely pressure, temperature, humidity and CO_2-content have to be measured accurately and the refractive index can then be calculated by means of the empirically determined Edlén formula. The estimated combined standard uncertainty of the updated Edlén formula itself was given as 10^{-8} [3]. In chapter 2 a 2D mask comparator is described, which operates by laser displacement interferometry in air and by optical line position sensing.

To achieve even smaller length measurement uncertainties, one has to perform displacement measurement by vacuum laser interferometry. In chapter 3 and 4 of this paper, such instrumentation developed in the PTB is described. Whereas the electron optical metrology system described in chapter 3 uses a fine scanning electron beam as a line position probe in vacuum, the nanometer comparator again uses line detection in air by means of an optical microscope. Thus, environmental conditions of the measurement object, as well as displacement measurement and line position detection can be varied upon application of the 3 different comparator types described in more detail below. This allows to investigate possible systematic differences which have to be taken into account to further reduce the measurement uncertainties as required.

2. Optical mask comparator

In the late 80´s, the PTB was involved in a development project of an industrial 2D mask comparator, the Leica LMS 2000. The main PTB task was to investigate the metrological capabilities of the instrument and to develop appropriate calibration procedures for length and x-y-coordinates of photomask standards. Since the beginning of the 90´s the PTB provided calibrated 2D position standards to customers world-wide (photomask standards, mainly with 152 mm (6´´) or 178 mm format (7´´)). Figure 1 shows the principle design of the LMS instrument, figure 2 shows a view on the comparator. The measurement object is mounted without further constraints on a kinematic 3-point support on a mask frame which rests on an x-y-stage. The movement of the air-bearing stage is realized by means of friction rod drives. The displacement of the object is measured by a two-axis plane mirror reference interferometer. A third interferometer axis is used as a so-called tracking refractometer, monitoring changes of refractive index of air. The detection of line position is based on the operation of a special confocal microscope for simultaneous x-y-coordinate measurements. The measurement uncertainties achieved for routine calibrations are listed in table 1 which summarizes the specifications for all instruments described here.

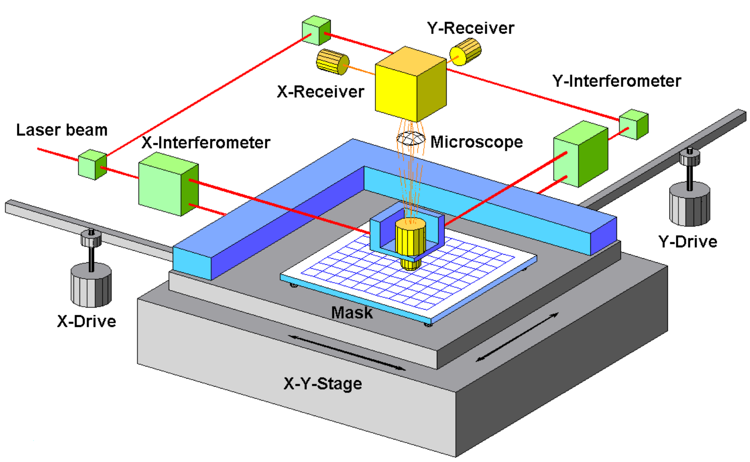

Figure 1: Basic design of the LMS mask comparator.

The LMS instrument was also used to investigate and develop error separation procedures for x-y-stage metrology, mask bending correction procedures, comparison measurements within the German calibration service (DKD) and an investigation of achieved long-term

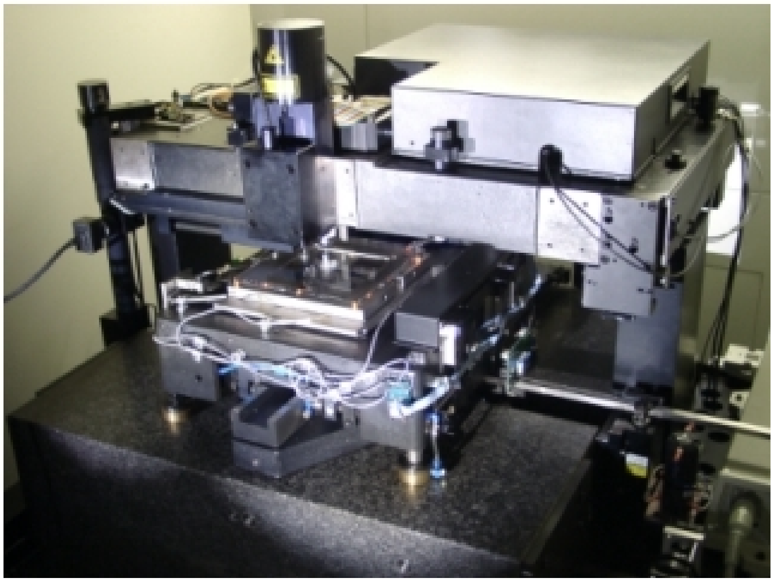

Figure 2: View on the LMS mask comparator.

reproducibility of photomask calibrations [4].

Moreover, the LMS was modified to allow measurements of objects with dimensions differing considerably from standard mask formats (stage travel range is about 230 mm x 200 mm). Examples of special objects which were measured in different specimen mountings do include line scales of 300 mm length used in the international line scale comparison Nano3, thin LCD glass substrates or optical reference plates of up to 270 mm in diameter.

For the calibration of even larger optical plates another set-up was developed in the PTB. It consists of a standard optical coordinate measuring machine equipped with an additional rotary table and a laser interferometer to measure the displacement of the line position sensing microscope in one axis with small uncertainty. The whole equipment is operating in air, see scheme in Figure 3 for illustration of the principle. The x-y-coordinate measurement applied in this case is the trilateration principle known from geodesy, i.e. the combination of multiple and mostly redundant high precision 1D length measurements in different orientations of coordinate grid points on a rigid structure [5].

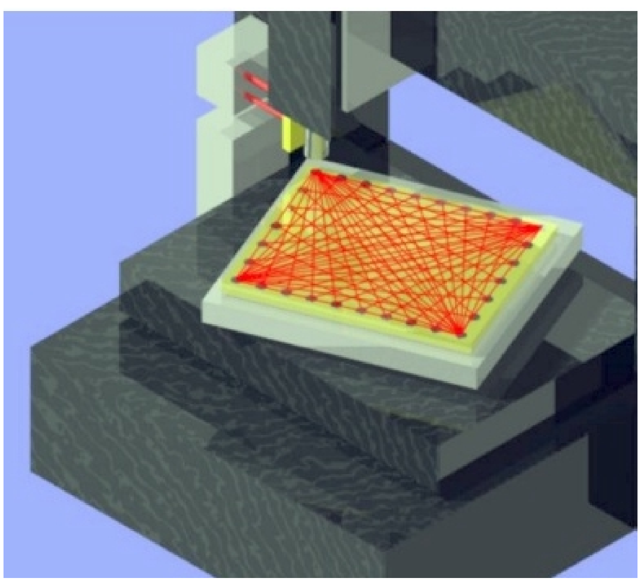

Figure 3: Illustration of multilateration set-up.

By means of this set-up calibrations of x-y-coordinates on optical plates with dimensions of up to 700 mm are possible. Achieved measurement uncertainties are estimated as 0,5 µm. Further reductions of measurement uncertainty would be possible by an improved instrument design and by application of two-wavelength interferometry schemes which compensate for refractive index changes of air [6].

3. Electron optical metrology system

The electron optical metrology system (EOMS) was developed in the middle of the 90´s to supplement and reinforce the mask metrology capabilities of the PTB. This was achieved mainly by application of a high resolution probe and displacement measurement by vacuum interferometry. The EOMS basically consists of a low energy e-beam scanning electron microscope mounted on top of a large vacuum chamber and an object stage capable to move 300 mm in x- and y-direction [7]. Figure 4 shows a view on the instrument while figure 5 illustrates the x-y-metrology design.

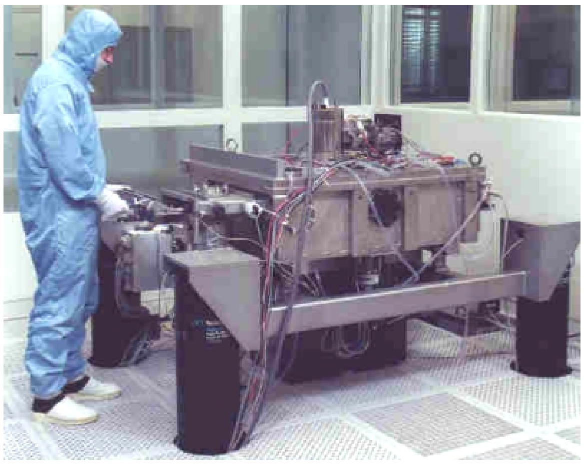

Figure 4: View on the EOMS.

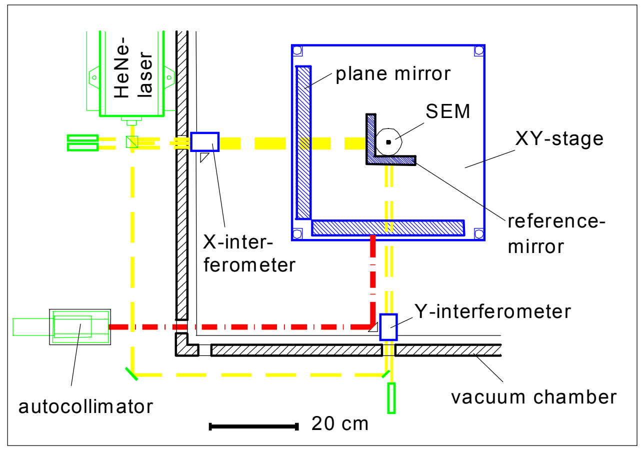

Figure 5: Metrology design of the EOMS.

So far, the EOMS was used for length and coordinate measurements and comparisons with the LMS [8] and also for measurements of width of small microstructures on masks and wafers and comparisons with other high resolution CD metrology tools like AFM and UV microscopy [9]. Generally speaking, the differences for CD measurement results found between EOMS and other microscopy methods on photomask and silicon wafer structures were smaller than 15 nm. Recently, the EOMS also was applied for calibrations of fine pitch standards which are widely used as calibration or magnification standards for SEM or SPM microscopes.

4. Nanometer comparator

The so-called nanometer comparator was designed to serve as the new 1D high precision length reference comparator of the PTB. It uses vacuum interferometry for displacement measurement of a carriage which in turn supports the measurement objects, like e.g. line scales. The travel range of the instrument was limited to about 610 mm in line with the arguments given in chapter 1. The target measurement uncertainty for high quality line scale calibrations on objects with small thermal expansion coefficient is 5 nm. The basic design elements of the instrument are shown in figure 6, whereas figure 7 provides a view on the equipment located in the dedicated measurement room of the PTB. The instrument was installed in the second half of 2000, it is planned to be used for calibration services in the end of this year.

The basic design principles of the instrument have already been reported before [10, 11]. To summarize shortly, the main points are:

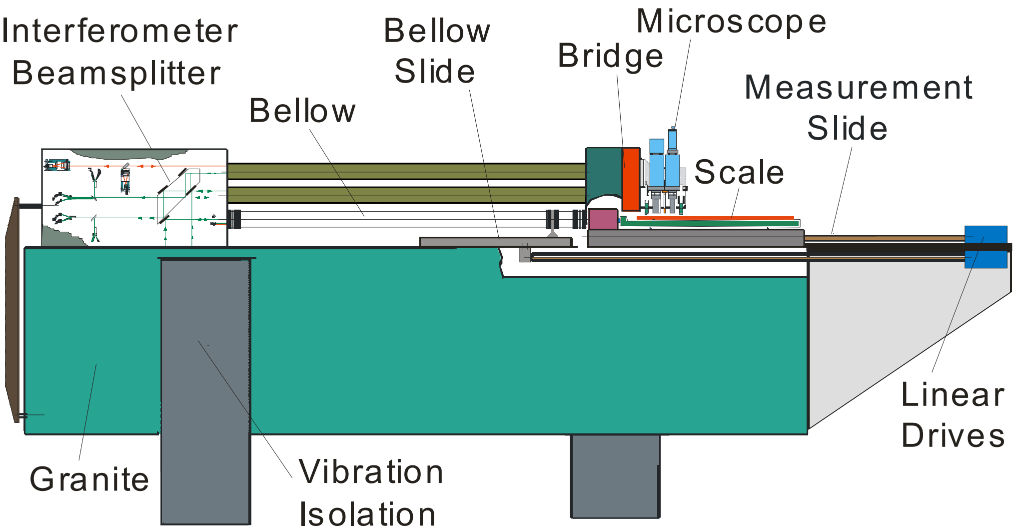

Figure 6: Basic design elements of the nanometer comparator.

- vacuum displacement laser interferometer with compensation of linear movements between interferometer beam splitter and microscope bridge during carriage translation as well as compensation of possible tilt of microscope bridge,
- heterodyne laser interferometer with spatially separated light feeding to the beam splitter in order to avoid frequency mixing errors,
- use of frequency doubled Nd:YAG laser for interferometry (532 nm, 100 mW output power),
- microscope bridge mount flexible to carry different line detection units, starting with two types of optical line position detection: CCD camera and photoelectric microscope,
- carriage supported and guided by air bearings and driven by linear drive system,
- possibilities to measure and control residual carriage guiding deviations (pitch, yaw, roll, y- and z-control),
- compensation of vacuum and bellow forces by second stage and compensation bellows,
- staggered air conditioning control systems for thermal stabilization of measurement chamber.

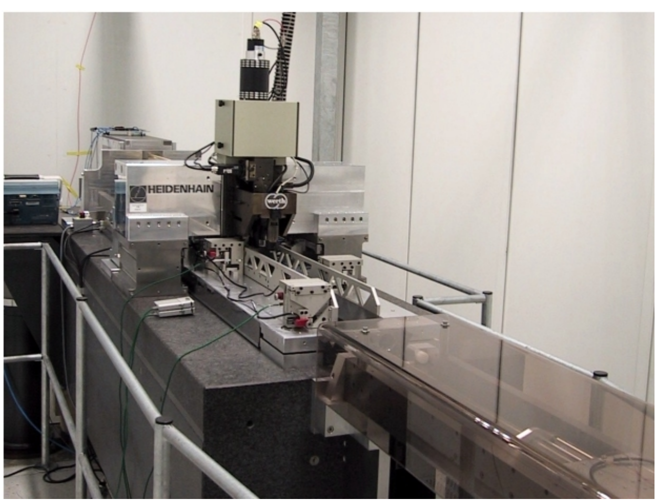

Figure 7: View on the nanometer comparator.

5. International line scale comparison Nano3

Initiated by the BIPM working group on nanometrology an international line scale comparison was prepared in order to document the current state of line scale calibrations on material measures of about 300 mm length with high quality chromium line graduations on it. This comparison should thus complement the older line scale comparisons refered to in the introduction. The comparison which is piloted by the PTB was started in May 2000 and it will end in spring 2002. 14 different NMI´s had agreed to participate in this comparison which used two line scales of identical layout but with two different substrate materials, namely Zerodur and quartz [12]. Care was taken to choose appropriate substrate handling to ascertain long-term stability of the scales. Attention was paid to have line scale graduations manufactured with optimized line edge quality, in order to minimize the influence of different microscopic line edge detection at the participating NMI´s as far as possible. Figure 8 shows the degree of coincidence of line edge position measurement after elimination of different length scales of the comparison results provided so far for a subset of NMI´s, which all have quoted a length-independent uncertainty contribution smaller than 20 nm. One can see, that although completely different types of optical microscopes with different line position detection procedures were used, the line position measurements showed good agreement.

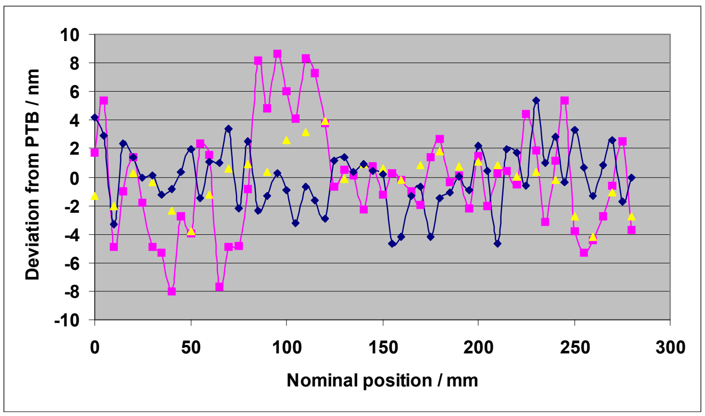

Figure 8: Agreement of Nano3 line scale measurement results for a subset of participants in reference to PTB after elimination of overall length scale differences (length scale differences may not be disclosed yet).

In addition to the line scales, also long gauge blocks were manufactured from the same basic material for independent determination of long-term stability as well as high precision measurement of important material parameters like thermal expansion coefficient and length compressibility. The measurements performed in an recently optimized gauge block vacuum interferometer allow to determine thermal expansion coefficients of longer gauges with uncertainties of $2{\cdot}10^{-10}\ K^{-1}$ [13].

6. Summary and outlook

We have described instrumentation which was and still is developed at the PTB to be used for high precision measurements on 1D and 2D material measures of length, namely line scales and photomasks. The actual and projected performance data of the instruments are summarized in table 1.

	LMS	Multilat.-CMM	EOMS	nm comparator*
Measurand	x-y-coordinates	x-y-coordinates	x-y-coordinates	length
Uncertainty (k=2)	$[(10\ nm)^2 + (0{,}2\ 10^{-6}\ L)^2]^{1/2}$	$[(0{,}5\ \mu m)^2 + (0{,}8\ 10^{-6}\ L)^2]^{1/2}$	$[(15\ nm)^2 + (0{,}08\ 10^{-6}\ L)^2]^{1/2}$	$[(4\ nm)^2 + (0{,}003\ 10^{-6}\ L)^2]^{1/2}$
Maximum Range	200 mm	700 mm	< 300 mm	610 mm

Table 1: Calibration uncertainties typically achieved or projected* on high quality 1D or 2D material measures of length with low thermal expansion coefficients

Further work will concentrate on a systematic comparison of different detection methods for single line and group of line graduations, different measurement strategies and their influence on the achievable measurement uncertainties and investigations of measurement object environment (air, vacuum) on overall length measurement uncertainty.

Acknowledgements

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