Characterization of an 100 nm 1D pitch standard by metrological SEM and SFM

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ABSTRACT

We report on investigations including calibration of a 100 nm pitch structure, the NanoLattice by VLSI Standards [1], with a special metrological scanning electron microscope (SEM) and a scanning force microscope (SFM). The SEM used is called electron optical metrology system (EOMS) and basically consists of a dedicated low voltage e-beam column which is mounted on top of a large vacuum chamber with an integrated, laser-controlled precision 2D stage [2]. The key feature of this instrument is the advantage to combine sub-nm-resolution object position measurement by vacuum laser interferometry with a high resolution e-beam probe of about 5-10 nm. Correlation methods combining the laser interferometer and secondary electron intensity profile data are used to analyze global pitch as well as local pitch deviations. The EOMS measurements confirm an excellent pitch uniformity. Preliminary estimations yield sub-nanometric mean pitch uncertainties for the 100 nm grating period over the whole active area of 1 mm x 1.2 mm. Additional SFM investigations were performed by a modified NanoStation III (SIS GmbH, Germany) which has been especially adapted for high stability measurements [3]. In this way, the instrument allows to determine pitch homogeneity and line edge roughness (LER) of the structures with high reproducibility. Preliminary results show a good agreement with EOMS measurements.

Keywords: scanning electron microscope, scanning force microscope, AFM, pitch calibration, correlation, Fourier series

1. INTRODUCTION

One- and two-dimensional gratings with calibrated submicrometer pitch are widely used to calibrate the magnification and to characterize image distortions of all types of high resolution microscopes, optical microscopes as well as scanning probe (SPM) and scanning electron microscopes. In recent years several commercial companies and research institutes have developed a number of transfer standards suited for calibration of high resolution microscopes [4], among them a whole set of standards especially adapted for SPM. This set – developed in an EU project [5] – also comprises lateral standards with a 2-dimensional pitch of nominally 100 resp. 300 nm (2D100, 2D300) that have been investigated accordingly e.g. at PTB [6].

In this contribution, a one-dimensional standard made of silicon with a nominal pitch of 100 nm was investigated, the NanoLattice standard by VLSI Standards Inc. Specimen material and topographic profile of this standard are optimized for high contrast imaging in a CD-SEM. A special feature of the NanoLattice is the option to mount the chip with the standard in a wafer-pocket on wafers with 150 mm, 200 mm or 300 mm diameter. The wafers are equipped with alignment marks and are compatible to automated wafer handling systems of CD-SEMs. The sample which was investigated here was mounted on a custom stub.

The main focus of this contribution is the calibration of mean pitch and pitch deviations with a special metrological scanning electron microscope in combination with correlation-based pitch evaluation routines. Global mean pitch can be measured by this method with a higher accuracy than by local pitch measurements. SFM measurements are used to determine line edge roughness and pitch homogeneity of the structures.

2. SEM MEASUREMENTS

SEM Instrumentation

The SEM used for these measurements, the electron optical metrology system (EOMS) [2], can briefly be described as a low voltage scanning electron microscope mounted on top of a large vacuum chamber which contains a specimen stage capable of loading planar measurement objects of up to 300 mm. The SEM was designed for 2D coordinate

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measurements at photomasks. This pitch calibration can be regarded as a special case of coordinate measurement, with a very small measuring grid and only one-dimensional structures.

The SEM electron column is optimized for low voltage operation. It features a thermal field emission cathode, an intermediate beam acceleration (beam booster), a magnetic-electrostatic detector objective lens (MEDOL), and an on-axis YAP scintillation SE detector which provides highly symmetric image contrasts without shadowing. Typical electron energy is 1 keV. The SEM was manufactured by ICT, Munich.

The xy-coordinate stage consists of a 'one-level-table' supported by four Teflon-pads, which moves on a lapped ground plate. The xy-stage is driven by two friction rod drives offering a travel range of 300 mm in both directions. The position of the xy-stage is measured by a double plane mirror laser interferometer with a resolution of about 0.6 nm. The measurement mirrors are fixed at the stage and the reference mirror is mounted at the conical objective lens of the SEM. In x-direction, displacements and yaw angle variations of the xy-stage are measured, whereas in y-direction only displacement is monitored. The interferometer is operating under high vacuum conditions, thereby eliminating the problems associated with interferometry in air (refractometry, air turbulences). The metrological frame of the instrument is shown in fig. 1.

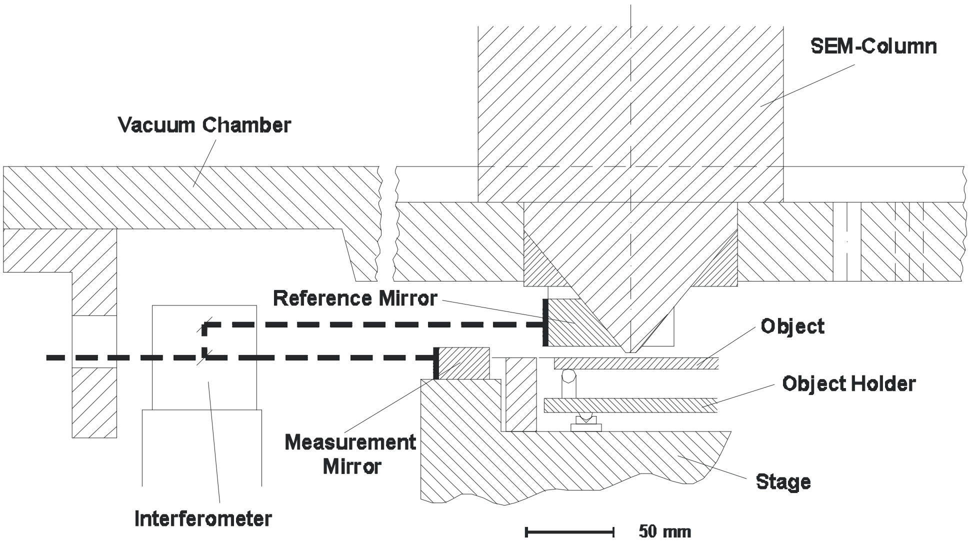

Fig. 1 Side view on metrological frame of EOMS

The laser interferometer controlled specimen stage is also used to calibrate the magnification of the scan field. Laser-interferometrical displacement measurements are performed at dedicated reference structures to determine magnification as well as scan field distortions. However, the scanfield calibration is not of high importance for this measurement because the maximum phase shift in the image that has to be determined for pitch evaluation is only about 30 pixels.

SEM Measurements

In principle, the precise knowledge of scan generator behaviour already allows to determine local pitches from single image scans. From such single scans, a local pitch value can be determined with uncertainties of about one nanometer. A smaller uncertainty for the global mean pitch within the measurement area can be obtained, if one uses the interferometrically measured stage positions to correlate the phases of SE intensity profiles determined within subsequent image scans. The phases of intensity profiles generated by vertical integration of SEM images were determined by correlation to a synthesized reference profile which was generated by approximation of a synthesized Fourier series to the measured intensity profile.

Image Aquisition and Phase Evaluation

SEM images of the pitch structure with 512x512 pixels, a field of view (FOV) of 1.6 µm and an electron energy of 1 keV are recorded (fig. 2). The greylevel-offset is approximated by a third order polynomial and substracted, the contrast is normalized to assure standardized conditions for data analysis. The intensity profile is averaged over 250 scan lines to reduce signal noise. Fourier series (Eq.1) is approximated to the signal profile with a given fundamental frequency ω corresponding to the reciprocal value of the nominal pitch value together with a magnification factor and a phase shift φ. The phase shift is the only free fit parameter in the approximation procedure. The resulting residual (i.e. the vanishing of higher order frequencies) is a criterion for truncation of the Fourier series.

$$f(x) = \sum a_n \cos(n\,\omega\,x + \varphi) + \sum a_n \sin(n\,\omega\,x + \varphi) \qquad (1)$$

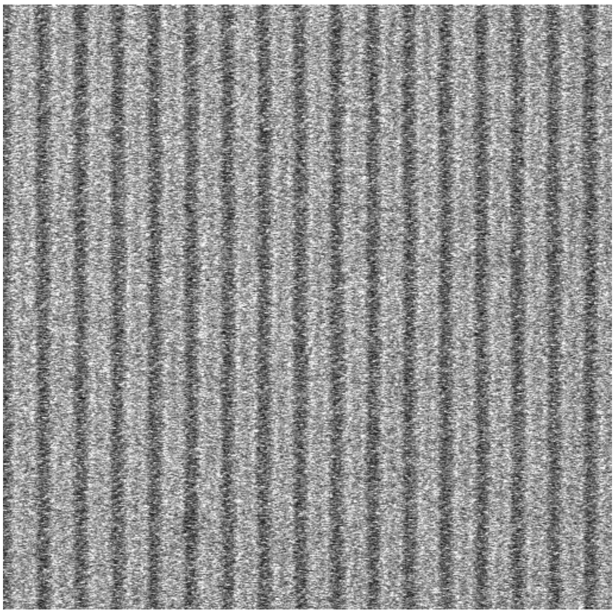

Fig. 2 SEM image of pitch structures, FOV 1.7 µm, electron energy 1 keV

In the Fourier series, a combination of sine and cosine is used because the duty cycle of the SEM intensity profile does not equal one. (This does not imply conclusions for the line-to-space ratio of the structure, CD measurements were are subject of this contribution.) As shown in fig. 3, the phase measurement is not based on a single structure but averages over several structures in the scan field. The evaluation of total phase shift is a combination of the correlation-based phase shift determination in the SEM images and the projection of the deviation of the real stage position from the design position (the stage positions are in the range of ± 50 nm).

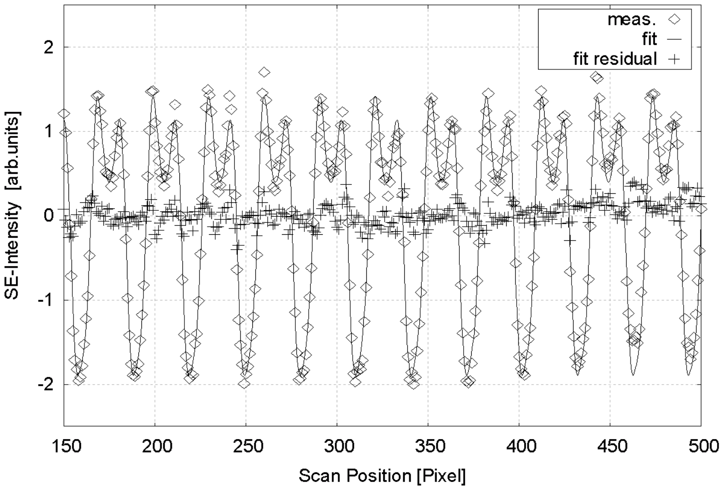

Fig. 3 Intensity profile of fig. 2, averaged over 250 scan lines. Displayed are the measured profile, the Fourier series approximation, and the fit residual.

Specimen Alignment

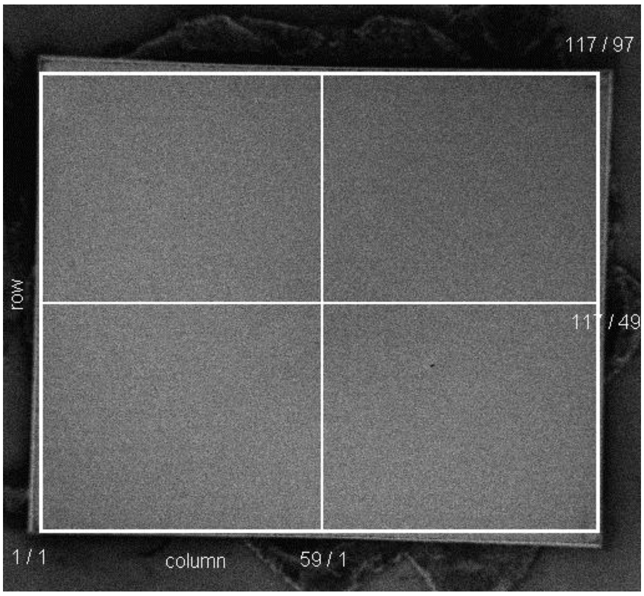

Fig. 4 SEM image (FOV 1.3 mm) of the standard, superimposed is a measuring grid with a step size of 10 µm.

The most time consuming part of the calibration of the pitch standard is the specimen alignment. For a pre-alignment, the chip is oriented along one axis of the SEM's xy-stage with a residual angle smaller than 2°. The object height is leveled with a residual angle smaller than 2 arc minutes. At the cutting edge of the chip, two characteristic, retrievable structures (e.g. conchoidal fractures) are chosen as alignment marks and a rough alignment angle α (between chip and xy-stage coordinate system) is estimated using laser interferometer data. (This step is not necessary for the wafer-mounted version of the NanoLattice standard which is equipped with alignment marks.) Because the chip's cutting edge is in general not parallel to the pitch structures, it is necessary to follow a single pitch structure to determine the correct alignment angle. This procedure is based on a successive approximation of the alignment angle: First, one follows a single pitch structure over a short distance with small-meshed measuring points. The phase shift in the images is calculated by fitting of Fourier series as described above. Phase shift together with deviation of stage position results in a corrected value for the alignment angle, but due to the small basis the residual error is still large. Therefore, the basis and the mesh size are successively increased, the corrected alignment angle is determined and fed back to the procedure. The procedure is continued until the end of the active area is reached. By this procedure, the alignment of the structures is related to the stage coordinate system (analogous to 2D coordinate measurements) with a residual error smaller 2 arc seconds. Next, a measuring grid of 97x117 measuring points with a meshsize of 10 µm is defined for the whole active area of the chip of 1.0 mm x 1.2 mm (see fig. 4). This grid is aligned to the pitch structures and defines the design coordinates for the measuring points. From fig. 4 it is apparent that the cutting edges of the chip are not parallel to the pitch structures.

Pitch Measurement

The actual pitch measurement is very similar to the alignment procedure, but now the measuring direction is not parallel to the pitch structures but perpendicular to it. The initial mesh size of the measuring points has to be an integer multiple of the nominal pitch. The procedure starts with small steps and calculates a preliminary scale factor for the pitch value. This pitch value is fed back to the procedure to continue with increased step sizes. The measured pitch value becomes more and more accurate with each iteration and the procedure stops when the opposite edge of the active area is reached. A chip of 1 mm size incorporates about 10,000 periodic structures with a pitch of 100 nm. As the phase shift error should be smaller than one period, we can estimate an uncertainty of about 10^{-4}.

SEM Results

Laser interferometer data were used to evaluate the offset of two SEM images. The phase shift which was determined by Fourier series approximation yields (in combination with the interferometer data) a scaling correction factor for the pitch. Iterated measurements resulted in a corrected mesh size of the measuring points of 9.9947 µm. For this value, the residual pitch deviation for the central area (row 38-60, resp. a band of 220 µm) became approximately zero (see fig. 5).

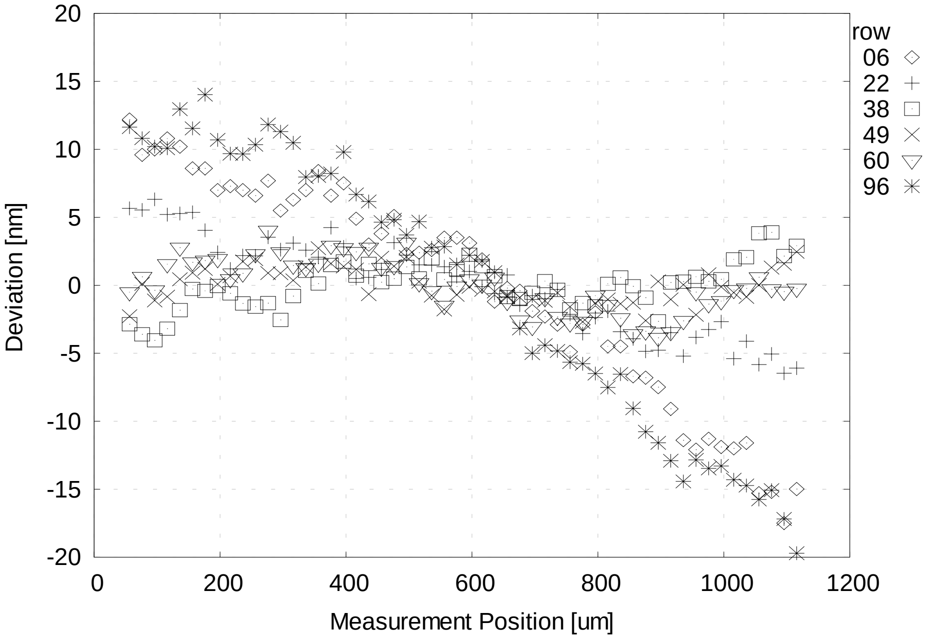

Fig. 5 Results of SEM pitch measurements. Displayed is the deviation from mean pitch (= 99.947 nm) as a function of measuring position.

From this it follows that the mean pitch value for the central area is 99.947 nm. Towards the upper and lower edge of the chip the mean pitch value increases and reaches a value of about 99.950 nm. This effect was confirmed by an independent measurement of structure straightness: In fig. 6 structure straightness for the left, central, and right area of the chip are presented which show deviations from straightness for the left and right area.

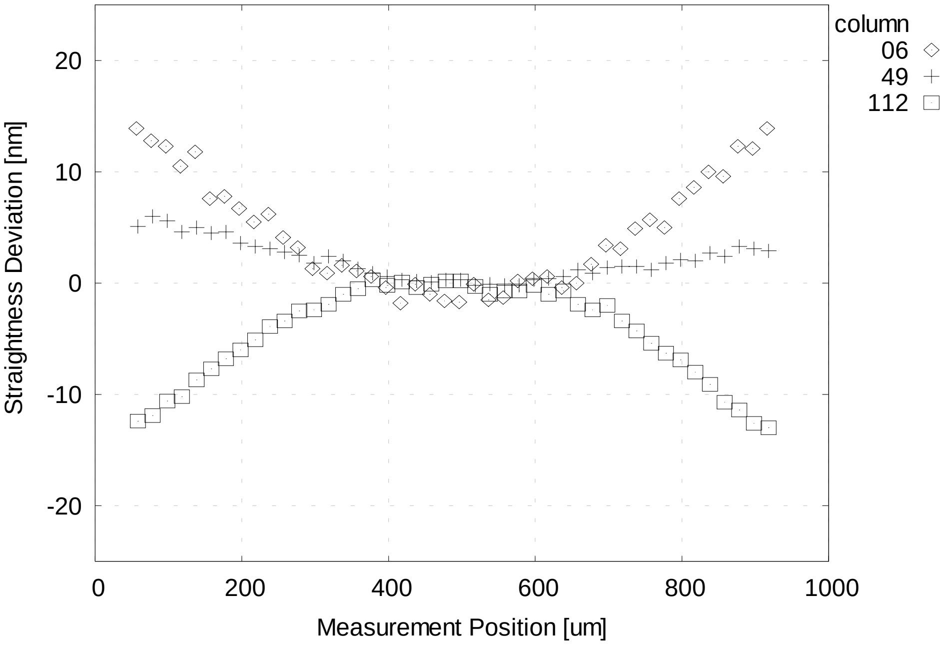

Fig. 6 Measurement of structure straightness for left, central and right area (column 06, 49, 112) of the chip. See fig. 4 for measuring coordinates.

A discussion of measurement errors reveals the main error contributions: The error due to phase calculation results directly from the Fourier series approximation and is smaller than 0.1 pixel (i.e. smaller than 0.32 nm). The uncertainty of the stage position is 1–2 nm (2σ rms). Corrections of the coordinate system like cosine-error, orthogonality, etc. can be neglected due to the small measurement range of 1 mm. The Abbe error results from the Abbe offset together with the guiding error of the xy-stage. For an estimation of the Abbe error, the measuring points were approached from random directions which led to random guiding errors in the range of 0.3 arc seconds. This yielded in a maximum Abbe error of 4 nm. The error due to limited stability of the electron beam is not estimated yet. In total, we estimate a preliminary error of 10 nm for a measuring length of 1 mm which leads to an uncertainty of 10^{-5} (2σ).

3. SFM MEASUREMENTS

Large-sample SFM in the PTB cleanroom centre

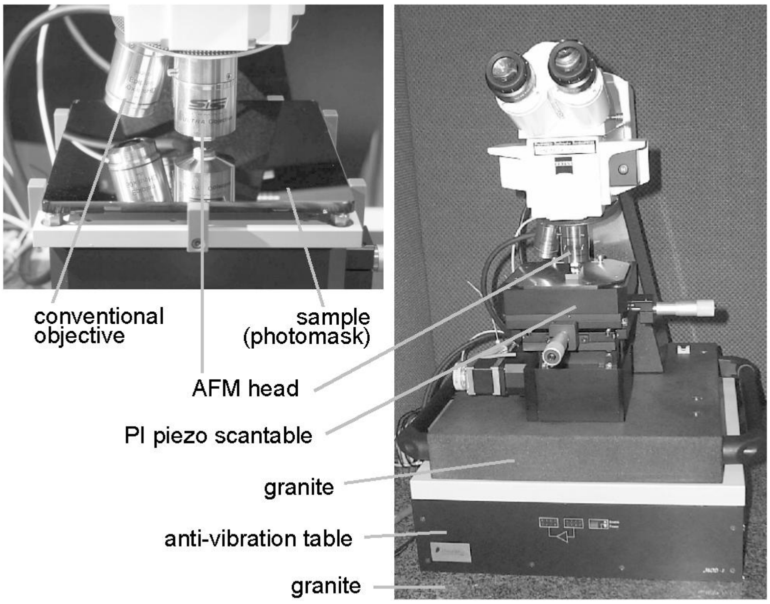

Fig. 7 The modified NanoStation III (SIS GmbH, Herzogenrath, Germany) combined optical and scanning force microscope in the PTB cleanroom center mainly used for the investigation of large objects. The system is housed in an acoustic chamber (visible in the background of the right photo).

The nano-lattice has, in addition to the EOMS investigation described above, also been studied by Scanning Force Microscopy (SFM). The system used here is a combined optical and Scanning Force Microscope that has been set up in the PTB cleanroom center for high-resolution characterization of photomasks and other – mainly large – technical objects (fig. 7).

The heart of the instrument is the UltraObjective^{TM} SFM head (S.I.S. GmbH, Herzogenrath, Germany) which is simply plugged into the turret instead of one of the optical objectives. Distance control is achieved by a glassfiber interferometer that measures the change of cantilever deflection at its end. The system can be operated both in contact and non-contact SFM mode.

As this system aims to ensure practical and comparatively fast operation at large objects up to 200 mm, it is not equipped with laser interferometry for position control and thus does not belong to the class of instruments directly traceable to the definition of the SI-unit meter. Instead, it is calibrated in regular time intervals either by physical transfer standards of by temporarily attaching laser interferometers to it [3].

While this system is consequently not used to certify absolute length values, special attention is devoted to its operating conditions to ensure that its maximum stability is exploited nevertheless.

The microscope is mounted on a granite support and rests on an active vibration-damping system (Halcyonics MOD-1, Göttingen, Germany). By shielding the apparatus with an acoustic chamber composed of an Al box with bituminous coating and cellular foam plastic insulation, an overall integrated noise-reduction to one third is achieved. A massive sample holder helps to reduce the influence of acoustic noise further.

Lateral scanning is performed with a piezo scanstage equipped with capacitive sensors for active position control (Physik Instrumente, Germany). The dynamic properties of this scanstage were carefully determined and turned out to be highly reproduceable. By applying individual correction factors for different scan ranges and scan speeds, the lateral measuring error can thus be reduced successfully.

As the acoustic chamber also acts as thermal insulator, it is essential to grand the system a sufficient idle time to make sure that the temperature in its interior reaches equilibrium. This is the crucial with respect to the comparatively long measuring circle as there are unavoidable heat sources in the chamber. The temperature behavior and its effects on the measurements have been studied in detail and are taken into account accordingly when plotting measuring schemes.

These three measures – vibration damping, capacitive sensors and ensuring that the system is operated in equilibrium – are the main prerequisites for high short-time and comparatively good long-term stability of this non-metrological instrument. They are observed in all measurements discussed here.

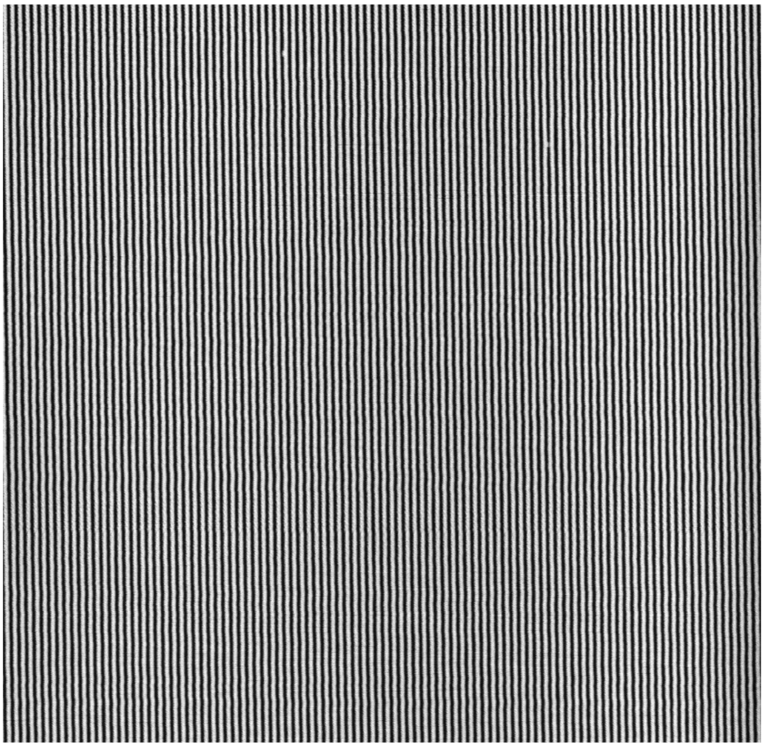

Fig. 8 Non-contact SFM image of the VLSI 100 nm 1D NanoLattice. Image size: 10 µm x 10 µm @ 1024 x 1024 pix

Measuring scheme

After mounting and aligning the measuring object optically, the system is always allowed 16 hours to reach its equilibrium before any measurements are started.

Prior to recording the “valid” image, a series of prescans uses to be performed at the respective location with the same scan parameters as in the subsequent actual measurement, taking about one hour. This is meant to ensure a stable dynamic scan behavior in the actual measurement. After recording the valid image, the probe uses to be withdrawn and the sample is – by means of micrometer screws – moved to the next measuring position, where the measuring series is continued after approximately one hour idle time.

As the total area of the nano-lattice of approx. 1,2 mm in x and 1,0 mm in y is by far too large to be imaged with sufficient resolution in acceptable time, a series of eleven equidistant non-contact SFM images of 10 µm x 10 µm were acquired from left to right (x-direction) in the middle of the respective lines (example in fig. 8). The step size between the measuring positions is 100 µm each, with the center of the first image being located 100 µm from the left edge of the nano-lattice.

The scan software presently used limits the resolution to 1024x1024 pix (i. e. here 9.8 nm/pix). The fast scan axis x is nearly perpendicular, the slow axis y nearly parallel to the line structures of the nano-lattice. As a compromise between the drift influences, that are the larger the slower scanning is performed, and image distortions, that grow with increasing scan speed, a scan rate of 0.2 lines/s was chosen.

In addition to this systematic series of images, further measurements have been carried out for verification and detail-analysis, e. g. line edge roughness.

Method of data analysis

To analyse the properties of the nano-lattice, the software package “Scanning Probe Image Processor” (SPIP, Image Metrology AS, Lyngby, Denmark) is applied, which provides a routine to determine the mean pitch and furthermore the deviations of the individual cell positions from the mean pitch by a process involving FFT, template finding of the characteristic periodic structure and cross-correlation [7, 8].

While this routine is primarily meant to analyse 2-dim grids, it would analyse a 1-dim grid in a way that each line of the object structure is treated as a unit cell extending all across the image. Consequently, only one global value for the position of each line as a whole would be delivered, while information on the straightness and roughness of the particular line would not be given. In order to force the routine to determine the position of each line at several locations, an artificially generated, perpendicularly oriented 1-dim grid of rectangular profile is therefore added to the original image data. The resulting 2-dim grid can then be analysed by the SPIP routine in the usual way.

Results

A typical example of the recorded (10 µm)² images is shown in fig. 8. The overall good uniformity of the nano-lattice is apparent. In the course of all SFM measurements, that total to an area of 0.002 mm² (of the whole 1.2 mm²), no broken line was found. Other major irregularities are also very rare. The line deformation visible in fig. 9 (left image) is already the severest case found of this kind of defect. As the other images in fig. 9 reveal, local contacts (extending over a no more than 200 nm) between neighboring lines do occur occasionally – in average one per (10 µm)² image – but the SFM images do not always allow to tell fabrication-related errors from possible contaminations that may have occurred later.

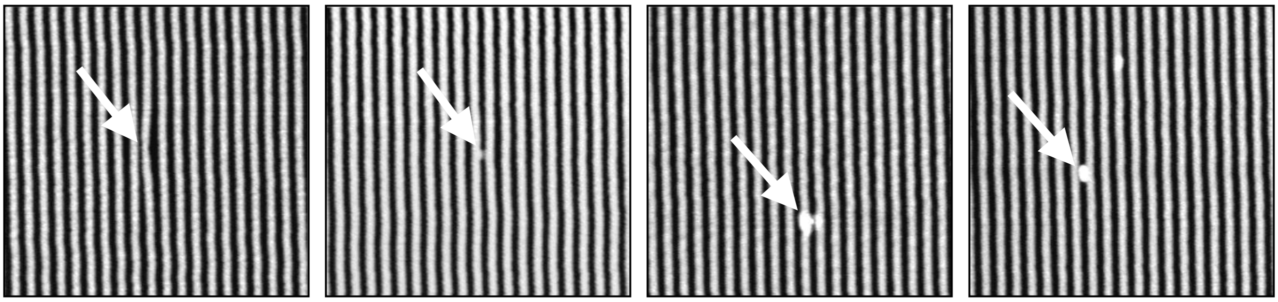

Fig. 9 nc-SFM images of some of the few irregularities distinguishable on the VLSI NanoLattice, size: (2004 nm)²

The uniformity of the nano-lattice within each of the (10 µm)² images has been analysed by the SPIP routine. As the measured lines have each been divided into 51 cells by the artificially generated perpendicular grid that has been added to the measurement data before applying the SPIP routine, the crosses in the diagrams of fig. 10 correspond to the position deviations of these individual cells from the calculated mean pitch. The size of the cells is thus approx. 100 nm (i. e. the pitch of the nano-lattice) times 195 nm (i. e. the artificial pitch).

Throughout the whole measurement series, no systematic sharp jump in the line position could be identified, but the distance between the lines seems to change gradually across the images, as can be seen e. g. in the bow from left to right in fig. 10a. This gradual variation – which was found in all images of this series – is, however, not to be attributed to the nano-lattice, but to the distortion of the image: Previous investigations of the dynamic behavior of the scan system have shown that a distortion of up to 2 nm within a 10 µm image is to be expected for a scan rate of 0.2 lines/s as chosen here. This was double-checked by changing the scan speed, and indeed, a different distortion was found then.

The position of the cells – i. e. the 195 nm sections of the lines – varies only statistically in x direction with a standard deviation of typically ±2 nm, which corresponds to only one fifth of a pixel. As J. F. Jørgensen et al. have proved mathematically and shown practically [8], the SPIP routine is under certain conditions capable of yielding sub-pixel resolution. In order to check whether this holds true also for this particular application, the position deviations in y direction have been plotted in fig. 10b. As this refers to an artificial grid of perfect geometry, the deviation should theoretically be zero; consequently, the standard deviation nevertheless visible in fig. 10b is to attributed to the insufficient pixel resolution and imperfections of the routine. From the fact that the position deviations in fig. 10b are significantly smaller than in fig. 10a we can conclude that the line sections – averaged over 195 nm along the lines – in fig. 10a actually vary statistically by a standard deviation of about ±2 nm as plotted here.

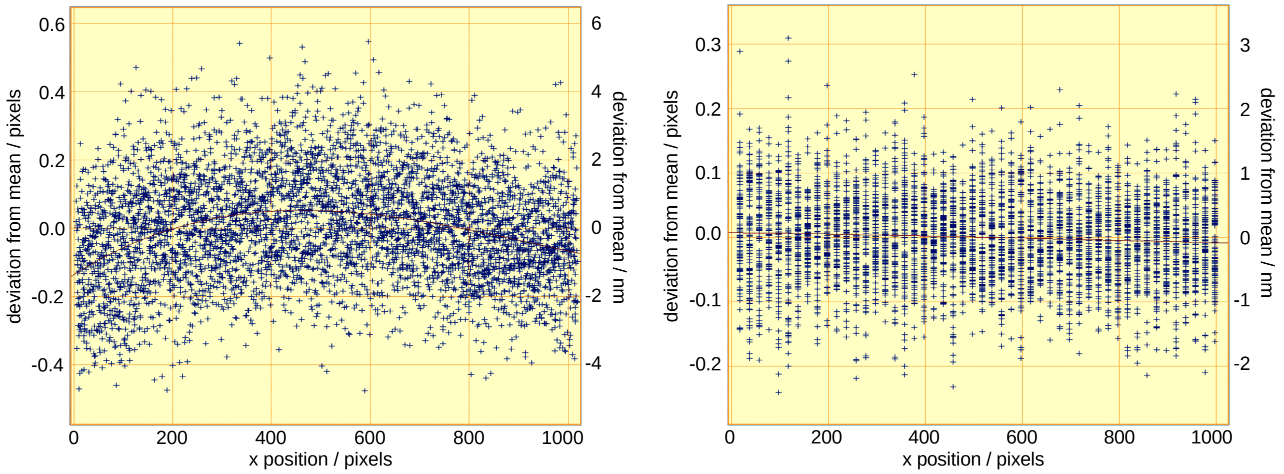

Fig. 10 a) Linearity analysis of the (10 µm)² image in fig. 8: lateral deviation of the individual positions of 195 nm long sections (defined here as artificial unit cells) of the nano-lattice lines from the mean pitch. The bow across the 10 µm (i.e. 1024 pix) does not originate from the nano-lattice but is the remaining non-linearity of the scan system. The plotted line section position deviations are thus mainly of statistical nature.

b) Verification of sub-pixel resolution of the SPIP routine: linearity analysis of the artificially generated perfect 1D grid of 195 nm pitch that has been added to the image data of fig. 8 with perpendicular orientation

The line edge roughness (LER) was further investigated by analyzing single lines. As criterion applied here, the edge position is defined as the point where the height reaches a value 5 nm (fig.11a) resp. 2.8 nm (fig.11b) below the maximum line height. While the LER values are affected by the tip shape only as far as the higher spacial frequencies are concerned, the line width values are systematically too high as no tip shape (mainly: tip width) correction has been applied here.

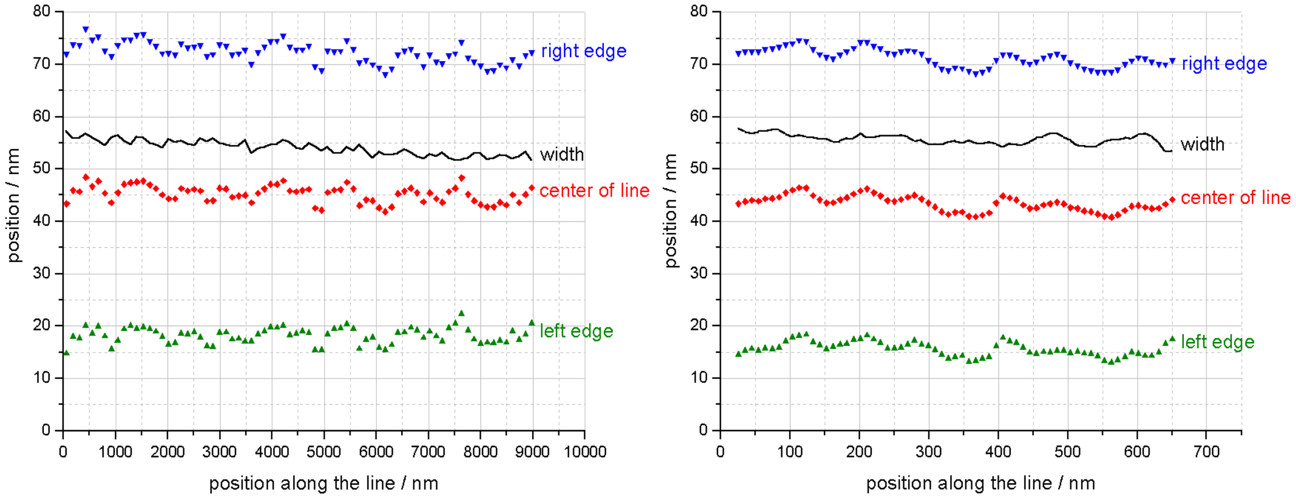

Fig. 11 Line edge roughness (LER) investigation: position of both edges and of the center of a line as derived from SFM measurements, line width (straight line); without tip shape correction; a) along a line in a (10 µm)² image, averaged over 117 nm (12 scan lines) each in steps of 117 nm, and b) along a part of a line in a (2 µm)² image scanned at 1024x1024 pix, averaged over 39 nm (20 scan lines) each in steps of 10 nm (5 scan lines)

The true line width can therefore be estimated to be significantly smaller than the measured ~55 nm; preliminary measurements (not shown here) with slim electron-beam deposited carbon needle probes actually yield a top line width of 25..30 nm.

In order to exclude that scanstage position fluctuations influence the LER results, averaging is performed over a sufficient number of scan lines. The edge positions plotted in fig.11a for a line in one of the (10 µm)² images were calculated after having averaged over 117 nm along the line; the LER measured here is between 1.58 and 1.90 nm (1σ), which agrees well to those approx. 2 nm derived from the SPIP analysis for 195 nm sections of the line. The LER values remain nearly unchanged when analysing an image recorded with much higher pixel resolution: fig.11b (2 µm x 2 µm image at 1024x1024 pix, averaged over 39 nm resp. 20 scan lines) yields a LER between 1.36 and 1.72 nm. The diagrams clearly reveal that the left and right edge positions vary mainly in the same sense.

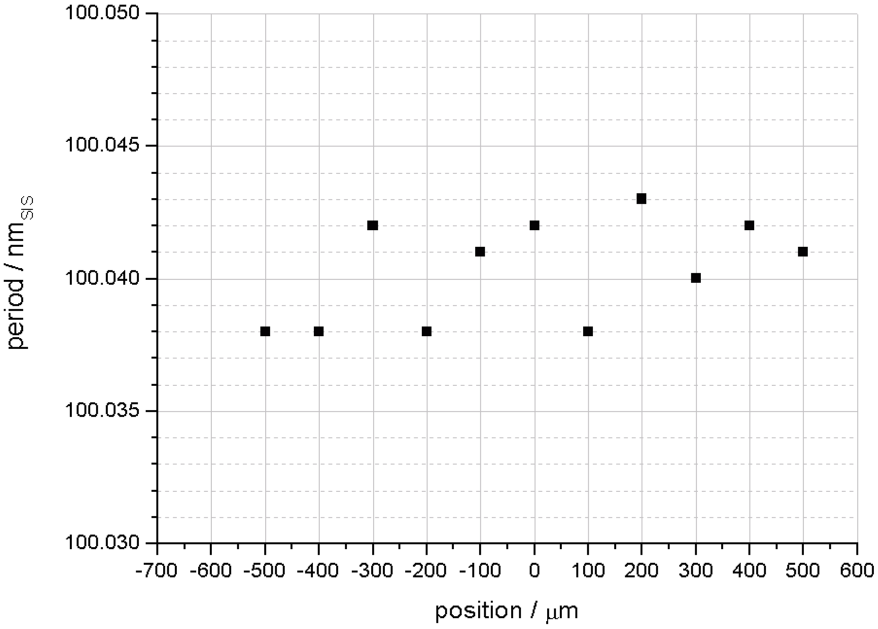

Fig. 12 The mean pitch values of all eleven (10 µm)² nc-SFM images recorded across the standard. Please note that the values stated here are uncorrected; the applicable calibration factors and the uncertainty are discussed in the text.

Fig. 12 shows the mean pitch of all 11 measurements of this series as calculated by the SPIP analysis. No systematic variation of the pitch can be identified across the standard. The pitch – averaged over a (10 µm)² image each – is remarkably stable and varies for only 5 pm. It has to be noted that such pitch values with a variation in the pm-regime can be obtained here – apart from strict adherence to the measuring scheme – only as a result of averaging: SPIP finally determines the positions of all 51 x 100 = 5100 cells in an image and deduces the mean pitch from this data.

It has to be added that the absolute values have an uncertainty much larger than the relative variation of values witnessed here, as the SIS large-sample SFM is not a metrology SPM. While the repeatability of this instrument under the strict measuring conditions defined above turned out to be in the order of some 10^{-5}, the reproduceability is in the order of some 10^{-4}: A second series of measurements at the same nano-lattice recorded one month later delivered a mean pitch value of 100.022 nm compared to 100.040 nm in the series discussed here; this is to be attributed to the lacking long-term stability of this SFM. Calibration measurements shortly before and after the measurements at this VLSI sample indicate that a correction factor of 0.9995±0.0005 needs to be applied here; we may therefore derive a mean pitch of (99.98±0.06) nm from these SFM investigations, which is in good agreement with the EOMS calibration result.

4. CONCLUSIONS

A method for SEM global mean pitch measurement with high accuracy was presented, with an estimated measurement uncertainty of about 10^{-5}. The investigated NanoLattice standard showed very good homogeneity over a wide range; only slight distortions in the range of about ±15 nm over a length of 1 mm could be observed.

SFM measurements confirmed the good homogeneity; no phase jumps could be detected. Furthermore, a comparatively low line edge roughness of usually below 2 nm (when averaged over ≥ 40 nm) was determined. Major irregularities such as interrupted lines were not found on the SFM-investigated total area of 0.002 mm²; other irregularities (e.g. local line distortions and line connections) are very rare. This standard is therefore well suited for high-precision calibration of SPM and other high-resolution microscopes. It thereby helped to confirm that the SIS SFM as a non-metrological SPM can be practically operated in the cleanroom center with an uncertainty as low as some 10^{-4} for the fast scan axis provided that a thorough calibration scheme has been executed before and that very strict measuring conditions are kept.

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