Title: ERROR SOURCE IDENTIFICATION IN DOT ARRAYS

Abstract: A method of error source identification in a dot array comprises the steps of generating a high-density grid pattern of nanoscale dots, for example dots of as little as 7 nanometres diameter at a pitch of 15 to 100 nanometres, on the surface of a substrate by an electron beam lithography machine in accordance with a design embodying a grid with the same dot pitch in two mutually orthogonal directions, i.e. a regular grid. Scanning electron micrographs (13) of individual sample areas of the generated array are then produced and the dot positions in each micrograph (13) and the displacements thereof from the dot positions in the design grid are determined, particularly with use of a fast Fourier transform and an estimated grid (12") representing the design grid, the estimated grid being recalculated as a best fit grid (12") in order to average the dot displacements. The determined displacements are evaluated to identify displacements indicative of systematic writing error and the source of the systematic writing error is identified by comparison of a frequency of the identified displacements with known or possible frequencies associated with errors occurring in machine operation.
ERROR SOURCE IDENTIFICATION IN DOT ARRAYS

The present invention relates to a method of error source identification in a dot array, especially a high-density dot array written by a pattern writing tool such as an electron beam lithography machine.

High-density dot arrays, namely grids of dots with regular pitch intervals in mutually orthogonal directions, have been produced for various reasons including creation of discrete magnetic storage zones or islands on data storage media such as hard drive discs of data processing equipment. Such dot arrays are written on suitable substrates, for example discs of about 6 centimetres diameter, in conformity with a design composed of an array of dots occupying a grid with the specified pitch intervals. By way of example, a high-density dot array on a substrate of that size may contain $1 \times 10^{13}$ dots with a dot diameter as little as 7 nanometres and pitch of 15 nanometres. Due to the nanometre tolerances in the dot pitch in an array written on such a substrate it is problematic to exclude inaccuracies in writing due to drift in the set operating parameters of the writing tool as a result of thermal influence and vibration and current fluctuations. Recognition of significant inaccuracies is often not possible until a product bearing a written array is placed in use, for example magnetically activated for data storage in the storage islands, and it is discoverable whether or not the desired storage result is achieved. In such circumstances it would be desirable to identify writing accuracies and remove error sources well before commitment to mass production of end products.

When patterns are written by typical boustrophedon scanning procedures in an electron beam lithography machine with conventional X-Y stage displacement of the substrate, thus writing successive pattern subfields in a main field by periodic beam deflection and blanking and then successive main fields with the help of stage X or Y displacement, the nominally stationary relationship of beam and stage which is periodically present allows test or diagnostic measurements to be taken to detect possible deviations in the written pattern from a design or master pattern digitally stored in the machine writing software. This can be carried out, for example, by the knife-edge procedure of partial blanking of the beam by a knife-edge wire to detect transmission current of the unblocked beam and, in particular, fluctuations in that current indicative of undesired relative movement of beam and substrate. The detected current fluctuations reveal frequencies which can be correlated with frequencies attributable to known error sources, such as mains current interference. However, beam placement errors in operation can be due to or amplified by dynamic
contributions such as synchronous noise produced by a pattern generator of the machine, drift induced by beam deflection and blanking, hysteresis of ferrites used in magnetic deflectors and slewing of deflection electronics. Dynamically sourced errors of these kinds cannot be detected by a detection procedure relying on static states of beam and substrate.

Although the described transmission current measuring method has serious limitations when employed for error detection in patterns written by machines with X-Y stage displacement, it would be effectively unusable in the case of a pattern or a dot array written by a machine with a rotary stage. Machines with X-Y stage displacement are not, in fact, practical or economically viable for writing high-density dot arrays of the kind described due to the time required to carry out complete scanning with the necessary exposure time - at least about 1 millisecond - for each dot and the consequent susceptibility to time-related drift in the nominally fixed operating parameters over the lengthy period between start and finish of writing and the traditional difficulties of accurate mating or stitching of pattern segments at subfield and main field boundaries. A machine with a rotary stage, in particular a stage which continuously rotates during writing and which itself is carried by a linearly displaceable sub-stage, may be able to distribute drift more favourably over a written pattern and to eliminate field stitching as well as reduce the overheads in stage movement and beam deflection. Dot arrays may be able to be written on concentric circular paths under continuous rotation of the rotary stage and substrate about an axis offset relative to the beam axis and periodic radial displacement of the rotary stage by way of the linearly displaceable sub-stage. The method covers dot arrays in a circular configuration as well arrays in orthogonal X/Y orientations. However, due to the constant stage rotation any errors present in the pattern would be mostly dynamic in nature and therefore undetectable by a method based on quiescent states of stage and substrate. Other measuring methods, for example with use of optical metrology tools, do allow measurement of mark placement errors relative to a design grid with the required level of accuracy, but do not provide the resolution needed to distinguish individual marks with diameters of only a few nanometres.

The principal object of the invention is therefore creation of an error source identification procedure by which writing errors in dot arrays, particularly those generated by writing tools such as electron beam lithography machines, may be able to be identified without some of the constraints of known methods, especially the problem of recognising dynamic errors and the inability to resolve high-density arrays.

A subsidiary object is use of the error source identification achieved by such a procedure to
influence writing tool operation to reduce or remove errors in subsequently written dot arrays.

Other objects and advantages of the invention will be apparent from the following description.

According to the present invention there is provided a method of error source identification in a dot array comprising the steps of generating a high-density grid array of dots on the surface of a substrate by a pattern writing tool in accordance with a design embodying a grid with a predetermined constant dot pitch in each of two mutually orthogonal directions, producing at least one scanning electron micrograph of an individual sample area of the generated array, determining the dot positions in the micrograph and the displacements thereof from the dot positions in the grid of the design, evaluating the determined displacements to identify displacements indicative of systematic writing error and identifying the source of the systematic writing error by comparison of a characteristic of the identified displacements with known or possible characteristics of errors occurring in tool operation.

Such a method allows relatively reliable identification of writing errors and particularly systematic writing errors, i.e. errors distinguishable from random or non-repeatable errors, in a high-density dot array of such a reduced scale that other methods may be unusable due to inadequate resolution or otherwise not satisfactorily usable due to, for example, predominance of dynamic components in the errors. Error identification is carried out with use of a sample area reflecting the writing result in at least a part of the generated array and by an approach, involving measurement and analysis by way of a scanning electron micrograph, allowing the level of resolution necessary for dots and dot pitches in the nanometre range, for example, dot diameters down to 7 nanometres and pitches down to 15 nanometres, or possibly micron range. The source of an identified systematic writing error can then be identified by associating a characteristic of the dot position displacements with characteristics linked with particular writing errors in tool operation, for example, noise, vibration and interference in a range up to 10 megaHertz.

The design grid will usually be a regular grid with the same dot pitch in both orthogonal directions, although different pitches in the two directions, i.e. X and Y directions in a Cartesian grid, are conceivable.

The dot array can be generated by different forms of tools, for example a tool in which the
substrate is stationary during writing action by the tool and periodic displacement of the substrate is carried out selectively in the two orthogonal directions, thus a tool with an X-Y stage. Alternatively, generation of the dot array can be performed with the substrate rotating about an axis during writing action by the tool and with periodic displacement of the substrate radially with respect to the axis, i.e. a tool with a rotary stage. In that case, use is preferably made of an electron beam writing the array at a rate of up to 10 megaHertz, although greater rates of writing are possible.

Although a single micrograph allows useful conclusions to be drawn, more effective identification of writing error in the generated dot array is achieved by producing a number of micrographs each of an individual sample area of the generated array, in which case the dot position and displacement determination and the evaluation to detect systematic writing errors are carried out in relation to each micrograph. It is then advantageous to evaluate the determined dot position displacements in the micrographs conjunctively to distinguish between displacements indicative of writing errors specific to one of the sample areas and displacements indicative of writing errors occurring in several of the sample areas. In the case of a writing tool with an X-Y stage the sample areas can be selected to lie along at least one axis parallel to one of the orthogonal directions, preferably also along at least one further axis parallel to the other one of the orthogonal directions, whereas if the dot array is generated by a writing tool with a rotary stage the sample areas can lie along at least one circular path concentric with the axis of substrate rotation as well as along at least one radius of the axis of substrate rotation. Assistance with subsequent isolation of specific sources of writing area may also be provided if the locations of the selected sample areas are recorded, for example specific subfields of the design when each area corresponds with a respective subfield.

For preference the step of determining the dot positions and position displacements comprises identifying the centres of area of the dots, which is preferably carried out by way of an algorithm applied to pixel data of the micrograph. The algorithm can be, for example, a fast Fourier transform providing a two-dimensional representation in which peaks denote the dot centres. In this connection, the or each micrograph can be produced by a scanning electron microscope having mutually orthogonal reference axes thereof aligned with the grid orthogonal directions of the generated array and the pixel data can denote intensity changes in the micrograph parallel to those directions.

Limitations on the accuracy of the microscope with respect to deflection calibration and to
achieving an absolute alignment of the reference axes with the grid directions of the generated array can be mitigated by identifying offset error in the micrograph due to rotation of the reference axes relative to the aligned directions and providing correction for the offset. Accelerating processing can be achieved, particularly when analysis of numerous micrographs is required, if the or each micrograph is analysed to define an estimated grid representing the design grid, in which case it is advantageous if the design grid is substituted by a best fit grid so located in relation to the design grid as to average the dot displacements. However, it remains possible to directly correlate the grid of the design with a grid defined by the determined dot positions. Accuracy can be further enhanced by identifying dot position displacements attributable to operating factors of a scanning electron microscope producing the micrograph and excluding those displacements from the evaluating step.

The dot position displacement can be expressed in various ways, but conveniently as a vector relative to a respectively associated dot position in the design grid, so that evaluation can be carried out by analysis of the vectors to recognise zones of similar vectors indicative of systematic writing error. It is, however, desirable to then distinguish systematic writing error due to periodically recurring influences from systematic writing error due to constantly present factors intrinsic to the tool or the environment. In a particularly preferred evaluation procedure, dot position displacement is plotted in dependence on time to identify at least one frequency indicative of systematic writing error, which opens up the possibility of identifying the error source by comparing the frequency with predetermined frequencies respectively associated with different causes of writing errors in tool operation. If the writing tool is an electron beam lithography machine, the predetermined frequencies can be indicative of, for example, power fluctuation, vibration, subsystem resonance and beam deflection errors.

In addition, the method can include the step of analysing the micrograph to determine the outlines of the dots in the sample area and utilising data relating to the determined outlines to influence dot outlines in dot arrays subsequently generated by the tool. The method can also be extended to multi-mode metrology by the additional steps of producing a coarse optical image of the generated dot array and analysing the optical image conjunctively with the micrograph or micrographs.

A further aspect of the invention consists of controlling a pattern writing tool, comprising the steps of by carrying out the method described in the foregoing with use of the tool to be
controlled and then correcting the tool operation to reduce or remove the identified error source in the subsequent generation of corresponding dot arrays by the tool. The tool in this further aspect of the invention is preferably an electron beam lithography machine.

An example of the method of the present invention will now be more particularly described with reference to the accompanying drawings, in which:

Fig. 1 is a diagram showing part of a design for a dot array to be written, with illustration of the direction of writing;

Fig. 2 is a diagram of part of a dot array generated by writing the design of Fig. 1 and illustrating, with exaggeration, irregular positions of the dots as represented by the dot centres;

Fig. 3 is a diagram showing the displacements of the centres of the dots of the array of Fig. 3 from the dot centres in the grid of the design of Fig. 1 and in a derivative best fit grid located to average the displacement;

Fig. 4 is a diagram showing the displacements of Fig. 3 as vectors; and

Fig. 5 is a diagram similar to Fig. 5, but of reduced scale and consequently greater area, showing a vector field with a zone indicative of a systematic writing error in the dot array.

Referring now to the drawings there is shown in Fig. 1 a design 10 of a dot array to be written by a writing tool, in particular an electron beam lithography machine which in this instance has a substrate stage displaceable in X and Y directions and which carries out writing of the array on a substrate carried by the stage by way of electron beam scanning of the substrate to write successive subfields of main fields of the array and periodic displacement of the stage to locate successive main fields in the scanning range of the beam. Scanning is carried out by beam deflection between the pattern features to be written, in this case the individual dots 11 of the array, and exposure of the substrate to the beam for the required time, the beam being blanked in the phases of stage displacement. The array could, however, be written by a machine with a rotary stage which rotates continuously about an axis while the beam spot periodically tracks the substrate moves with the stage to write dots on a circular path concentric with the substrate rotation. In such a
procedure, after writing a dot on the path the beam is deflected in opposite sense to the
direction of rotation to commence tracking for writing the succeeding dot on the path. The
stage together with substrate can be moved radially of the axis of rotation to place the beam
on radially successive concentric paths. Dot array writing in this manner may offer
significant throughput advantages by comparison with writing with an X-Y stage, particularly
where high-density arrays in a nanometre scale are generated on relatively large
substrates.

In the present case, by way of example only, writing is carried out on the X-Y stage machine
with the beam energy set to 100 kiloelectronVolts and a final aperture of 50 microns. With a
beam main field resolution of 18 bits and maximum field size of 0.262 millimetres the dots
11 can be written at, for example, a 5 nA beam current with a 1 nanometre placement
resolution. The main fields and subfields are square sides of, respectively, 16.4 microns
and 4.096 microns. In the design, the dots have a diameter A of 7 to 50 nanometres and
are placed on a regular grid 12 - the design grid with respect to the writing error detection
process described in the following - defining a dot pitch B of 15 to 100 nanometres in each
of X and Y directions. A subfield of the stated size contains, for example, 1600 dots at a
pitch of 100 nanometres, increasing to 26,569 dots at a pitch of 25 nanometres. Each dot
11 is defined by a shape composed of 1 to 10 exposure elements and the dots are written
by a boustrophedon scanning procedure commencing, as shown in Fig. 1, in the lower left
corner and meandering along an X axis while incrementing one row along the Y axis on
each change in X direction. The substrate consists of a GaAs wafer coated with a 50
nanometre thick layer of baked hydrogen silsesquioxane applied, diluted in a solvent, by
spinning to provide an electron-sensitive resist. After exposure to the beam for writing of
the array, the wafer is developed in tetramethyl ammonium hydroxide and washed.

The described dimensions, parameters and procedures are, as stated, by way of example
only and merely serve to illustrate a suitable process for generation of a dot array of a kind
appropriate for use in, for example, production of a hard drive disc with magnetic storage
islands arranged in similar manner to the dots.

A high-density dot array with dimensions in the mentioned ranges is susceptible to writing
errors due to disturbances in the machine operation, whether due to fluctuations in current,
thermal effects, vibrations, subsystem resonances or other sources of noise. Such writing
errors manifest themselves particularly as displacements in dot position or variations in dot
pitch relative to the dot positions or pitches in the grid of the design. The errors can occur
randomly due to transient effects, but also repeatably or systematically when the source is a noise such as one of the kinds mentioned. Identification of errors and attribution to specific sources allow remedial action to be taken, i.e. correction of the machine operation to remove or at least reduce the error, before committing to creation of end products. In order to detect writing errors, both random and systematic and to distinguish the latter from the former, a number of sample areas of the substrate bearing the written array is scanned by a scanning electron microscope to produce a micrograph or image of each area and with the X and Y axes of the grid of the array approximately aligned with X and Y references axes of the microscope. Part of a micrograph 13, showing a small number of dots in the sample area, is shown in Fig. 2. The sample areas, which in the present example arbitrarily correspond with individual subfields, can be selected to have random disposition or to lie on X and Y axes. Each micrograph produced is digitised to provide a database of, for example, 2,048 x 1,536 pixels with 256 grey levels and is stored.

Analysis of the scanning electron micrographs or images can now be carried out to determine the positions of the imaged dots 11 in each sample area of the array, for which purpose a two-dimensional fast Fourier transform of each image is calculated and evaluated to provide information on the distribution and orientation of features of the sample area, in particular the dot centres 14 - representing centres of dot area - of the dots in the sample area. The analysis is carried out by way of a program in which, on the basis of a series of images presented, the need for image-specific information such as magnification or actual pitch of the dots is eliminated so as to allow automatic operation of the program for batch analysis of large numbers of images. This provides a substantial saving of computation time by comparison with direct correlation of micrograph data with data describing the grid of the design, although direct correlation remains an alternative possibility as a basis for micrograph analysis. Initially, a Hanning window function is applied to the image to reduce the effects of a non-integer number of dots spanning the image height and width. The fast Fourier transform, implemented in the program, is employed to create a two-dimensional representation of the image of the array. The 2,048 pixels of the image width correspond with an integer power of 2, but the 1,536 pixels of the image height do not and if the transform is used on an image which does not have dimensions in pixels equal to an integer power of 2 the algorithm appropriately pads the data with zeros.

The transform places the zero frequency point in the lower left of the resulting two-dimensional representation of the array. Since it is customary to place this point in the centre for image display, the results are shifted to place the origin in the centre.
transform shows a peak in the centre at zero frequency corresponding with the overall intensity level in the image. The first peaks encountered when moving along the X and Y axes from the centre correspond with the fundamental dot spatial frequencies. The offset of the first peak along the X axis in Y direction signifies X rotation in the sense of rotation of the Y axis of the dot grid relative to the reference Y axis of the microscope and thus of the micrograph. Similarly, the offset of the first peak along the Y axis in the X direction corresponds with the Y rotation. The peaks in the transform arise from the contributions of each of the dots and variations in the dot positions from a regular grid cause the peaks to be broadened. A centre of gravity of each peak was calculated using values above half the maximum peak height, the centre of gravity of the peak representing the average dot pitch and the position of the maximum peak value representing the most common pitch. The expected position of each of the dots in the image can be calculated, with double precision, from the X and Y offsets, rotations and dot pitches, thus defining an estimated grid 12\', as shown in Fig. 3, of the design, from which the design grid position of each dot in the micrograph can be calculated.

In the case of a high microscope magnification resulting in only a few dots, for example 10 or less, spanning the image (which can be used to evaluate dot outlines) the estimated grid 12' calculated from analysis of the transform may be liable to exhibit larger position, scale and rotation errors than expected from statistical variation, apparently as a consequence of application of the transform to a non-integer number of dot pitches spanning the image. These errors can be eliminated, or rather averaged, by recalculating the design grid as a best fit grid 12" with respect to observed positions where grid position, scale and rotation are optimised.

In the program the specific position of each dot in the image is found by convoluting the expected two-dimensional intensity profile of an individual dot with a rectangular area of the image centred on the expected dot position. Since the expected dot position is not, in general, an integer number of pixels a bipolar interpolation of the image is used. The rectangular area of the image searched has a width equal to the dot size in X direction and a height equal to the dot size in Y direction. The intensity profile of the dot, which can be generated algorithmically as a Gaussian profile in any radial direction from the centre, varies in dependence on the particular resist provided on the wafer forming the substrate. The individual dot position is taken as a point in the convolution with the maximum value, which is obtained with sub-pixel accuracy by use of a bi-cubic interpolation of the convolution with the fit being made to the 4 x 4 pixels around the point in question.
The dot positions in the image are determined in terms of the image itself, thus in pixels in the case of the digitised data of the micrograph, and the pixels are converted to distance in nanometres. The average dot pitch will match the pitch in the grid of the design to a high degree of accuracy in view of the fact that calibration of the subfield deflection of the beam in the machine is normally carried out with use of laser interferometry over distances close to the full deflection range and with a mark located to within a few nanometres in each of the corners of the deflection field. The residual scale error can be less than 0.1%, which is generally more accurate than relying on the distances reported by the microscope. Consequently, the conversion factor translating pixels in the image to distance in nanometres is taken as (average measured pitch in pixels) / (intended pitch). From this there can be obtained a vector plot of the image showing, as vectors, the displacements of the positions of the dots in the image from the estimated grid 12' of the design, part of such a vector plot being shown in Fig. 4 with vectors identifying the displacement of each dot relative to the grid 12'. Zones in which vectors 15 exhibit a pattern similarity, as indicated by the zone 16 in the lower righthand corner area in Fig. 5, are indicative of systematic error as distinct from randomly occurring error due to transient influences. The greater proportion of systematic error may, in fact, be due to intrinsic aspects of the machine, such as imperfections in laser interferometry mirrors used to determine stage position and magnetic fields associated with the stage, and sources of this kind are to be distinguished from sources such as vibration, noise and interference causing systematic error occurring on a non-repeatable basis in a small area. A repeating pattern of errors of the latter kind can be detected by a suitable sampling procedure.

It is also possible to carry out further analysis of the micrograph to determine the outline of each dot, in particular at magnifications where each dot occupies numerous pixels, by employing a procedure in which the video level at the observed dot position is taken as a maximum and the average video level at four points halfway between the observed dot position and the neighbouring dots is taken as the minimum. All angles, having a given angular increment around a dot are then considered in turn and for each angle the dependence of the video intensity on radial distance from the observed dot position is extracted up to a distance of half the pitch of the dot. The data are mirrored on the other side of the origin and a Gaussian profile is fitted to all the data, the point at which the fitted curve reaches the 50% level being taken as the position of the dot edge. The dot outlines assessed in this manner may be found to consistently depart from pure circles and the assessed departures from true circular shapes may be used in assessed writing
performance of the machine, planarity of the resist and other influencing factors able to be taken into account in possible corrections.

In the course of determination of dot positions, consistently large errors in the X direction, likely to be attributable to flyback of the microscope raster scanning from left to right during micrograph acquisition, could be observed on the lefthand side of each micrograph. Accordingly, data relating to this part of the micrograph was excluded from the analysis. Any errors due to scan distortion around the centre of the field can be assessed by comparing micrographs of the same sample area within the written array at each of the orientations 0, 90, 180 and 270 degrees with respect to the microscope reference axes. In such a comparison, an image area of the dot array consisting of 81 x 81 dots on a pitch of 50 nanometres is approximately centred on the micrograph scan. The images are first rotated so as to compensate for any rotation of the sample from 0 degrees and only then are analysed. These errors in microscope scanning accuracy may also be able to be reduced or eliminated to some extent by use of a microscope with greater scanning accuracy.

A preferred procedure for linking the error forms evident from the determined dot displacements relative to the dot positions in the design grid consists of plotting the dot position errors in order of dot exposure against time with knowledge of the dot writing rate by the machine and generating a fast Fourier transform of the dependence of dot placement errors on time, particularly with the object of finding high-frequency noise and interference which may be applicable not only to machines with X-Y stages, but also machines with rotary stages. The transform revealed, in test examples, frequencies of 160 and 220 Hertz (in the case dots written with 5 nA current) known to be attributable to machine subsystem resonances activated by movements of the X-Y stage. Other identifiable frequencies occurring in the transform were 50 Hertz, which corresponds with mains frequency, and 800 Hertz due to the vibrations in operation of a vacuum pump of the machine. Frequencies attributable to dynamic error sources such as those associated with a rotating stage and substrate can be identified in the same manner. In the case of errors specific to a machine with an X-Y stage, such as subfield calibration and field stitch errors, it is possible to identify these errors by placing the point where the corners of four adjacent subfields meet in the centre of the micrograph and selecting dots from a quadrant of each subfield. Any deflection field scale and rotation errors will cause recognisable discontinuities across the field boundary. Once systematic writing error sources have been identified by frequency association, action can be taken to eliminate or reduce the influence of those sources, for
example corrective action on the beam deflection control variables.

A method exemplifying the invention allows accurate detection of dot positions in a high-density dot array by sampling with electron scanning microscope images, analysis of the images and then, on the basis of the detected dot positions, determination of dot displacements relative to the dot positions in the design grid, which, in a preferred procedure, is simulated in a program by an estimated grid derived from the images themselves. The dot displacements can then be subjected to analysis to identify errors due to periodic influences on writing operation. It is accordingly possible to establish, in advance of commitment to large-scale output of written dot arrays, the accuracy of the writing and on that basis to undertake measures to improve accuracy so as to create products more closely meeting the original design requirements.
CLAIMS

1. A method of error source identification in a dot array comprising the steps of generating a high-density grid array of dots on the surface of a substrate by a pattern writing tool in accordance with a design embodying a grid with a predetermined constant dot pitch in each of two mutually orthogonal directions, producing at least one scanning electron micrograph of an individual sample area of the generated array, determining the dot positions in the micrograph and the displacements thereof from the dot positions in the grid of the design, evaluating the determined displacements to identify displacements indicative of systematic writing error and identifying the source of the systematic writing error by comparison of a characteristic of the identified displacements with known or possible characteristics of errors occurring in tool operation.

2. A method as claimed in claim 1, wherein the design grid is a regular grid with the same dot pitch in both orthogonal directions.

3. A method as claimed in claim 1 or claim 2, wherein the step of generating is carried out with the substrate stationary during writing action by the tool and with periodic displacement of the substrate selectively in the two orthogonal directions.

4. A method as claimed in claim 1 or claim 2, wherein the step of generating is carried out with the substrate rotating about an axis during writing action by the tool and with periodic displacement of the substrate radially with respect to the axis.

5. A method as claimed in claim 4, wherein the step of generating the array is carried out with an electron beam writing the array at a rate of up to 10 megaHertz.

6. A method as claimed in any one of the preceding claims, wherein the step of generating is carried out with an electron beam forming each dot of the array from 1 to 10 exposure elements.

7. A method as claimed in any one of the preceding claims, wherein the step of producing the at least one micrograph comprises producing a plurality of micrographs each of an individual sample area of the generated array, the subsequent steps of determining and evaluating being carried out in relation to each micrograph.
8. A method as claimed in claim 7, wherein the step of evaluating comprises evaluating the determined dot position displacements in the micrographs conjunctively to distinguish between displacements indicative of writing errors specific to one of the sample areas and displacements indicative of writing errors occurring in several of the sample areas.

9. A method as claimed in claim 7 or 8 when appended to claim 3, wherein the sample areas lie along at least one axis parallel to one of the orthogonal directions.

10. A method as claimed in claim 9, wherein the sample areas lie along at least one further axis parallel to the other one of the orthogonal directions.

11. A method as claimed in claim 7 or 8 when appended to claim 4, wherein the sample areas lie along at least one circular path concentric with the axis of substrate rotation.

12. A method as claimed in claim 7 or 8 when appended to claim 4 or in claim 11, wherein the sample areas lie along at least one radius of the axis of substrate rotation.

13. A method as claimed in any one of claims 7 to 12, wherein the locations of the sample areas of the generated array are recorded to provide data for assistance with identification of writing error sources.

14. A method as claimed in any one of the preceding claims, wherein the step of determining the dot positions comprises identifying the centres of area of the dots.

15. A method as claimed in claim 14, wherein the dot centres are determined by way of an algorithm applied to pixel data of the micrograph.

16. A method as claimed in claim 15, wherein the algorithm is a fast Fourier transform providing a two-dimensional representation in which peaks denote the dot centres.

17. A method as claimed in claim 15 or claim 16, wherein the or each micrograph is produced by a scanning electron microscope having mutually orthogonal reference axes thereof aligned with the grid orthogonal directions of the generated array and the pixel data denote intensity changes in the micrograph parallel to those directions.

18. A method as claimed in claim 17, wherein the step of determining comprises
identifying offset error in the micrograph due to rotation of the reference axes relative to the aligned directions and providing correction for the offset.

19. A method as claimed in any one of the preceding claims, wherein the step of determining comprises analysing the micrograph to define an estimated grid representing the design grid.

20. A method as claimed in claim 19, wherein the design grid is substituted by a best fit grid so located in relation to the design grid as to average the dot displacements.

21. A method as claimed in any one of claims 1 to 18, wherein the step of determining comprises correlating the grid of the design with a grid defined by the determined dot positions.

22. A method as claimed in one of claims 19 or 21, wherein the step of determining comprises identifying dot position displacements attributable to operating factors of a scanning electron microscope producing the micrograph and excluding those displacements from the evaluating step.

23. A method as claimed in any one of claims 19 to 22, wherein each dot position displacement is expressed as a vector relative to a respectively associated dot position in the design grid.

24. A method as claimed in claim 23, wherein the step of evaluating is carried out by analysis of the vectors to recognise zones of similar vectors indicative of systematic writing error.

25. A method as claimed in claim 24, wherein the step of evaluating comprises distinguishing systematic writing error due to periodically recurring influences from systematic writing error due to constantly present factors intrinsic to the tool or the environment.

26. A method as claimed in any one of the preceding claims, wherein the step of evaluating comprises plotting dot position displacement in dependence on time to identify at least one frequency indicative of systematic writing error.
27. A method as claimed in claim 26, wherein the step of identifying the error source
comprises comparing the frequency with predetermined frequencies respectively associated
with different causes of writing errors in tool operation.

28. A method as claimed in claim 27, wherein the tool is an electron beam lithography
machine and the predetermined frequencies are indicative of power fluctuation, vibration,
subsystem resonance and beam deflection errors.

29. Apparatus as claimed in any one of the preceding claims, comprising the step of
analysing the micrograph to determine the outlines of the dots in the sample area and
utilising data relating to the determined outlines to influence dot outlines in dot arrays
subsequently generated by the tool.

30. A method as claimed in any one of the preceding claims, comprising the additional
steps of producing a coarse optical image of the generated dot array and analysing the
optical image conjunctively with the micrograph or micrographs.

31. A method of controlling a pattern writing tool, comprising the steps of carrying out
the method as claimed in any one of the preceding claims with use of the tool to be
controlled and correcting the tool operation to reduce or remove the identified error source
in the subsequent generation of corresponding dot arrays by the tool.

32. A method as claimed in claim 30, wherein the tool is an electron beam lithography
machine.