However, depending on the application of the projection unit, defects may be tolerable up to a certain degree. Thus, the quality of the projection units needs to be assessed in order to guarantee that the respective quality criteria are met by the projection unit.

Thus, the object of the invention is to provide a method as well as a system for assessing the quality of micro- and/or subwavelength-optical projection units.

Summary

According to an aspect, the present disclosure refers to a method for assessing the quality of a multi-channel micro- and/or subwavelength-optical projection unit, comprising the following steps:

illuminating at least a predefined portion of the multi-channel micro- and/or subwavelength-optical projection unit so that an image is generated by at least two channels of the predefined portion of the multi-channel micro- and/or subwavelength-optical projection unit;

- capturing the image generated by the predefined portion of the multi-channel micro- and/or subwavelength-optical projection unit;

- analyzing the image;

- determining at least one characteristic quantity based on the analysis of the image, wherein a value of the characteristic quantity is associated with at least one characteristic feature of the multi-channel micro- and/or subwavelength-optical projection unit, at least one defect of the multi-channel micro- and/or subwavelength-optical projection unit and/or at least one defect class of the multi-channel micro- and/or subwavelength-optical projection unit; and

- assessing the quality of the multi-channel micro- and/or subwavelength-optical projection unit based on the at least one characteristic quantity;

wherein the image of the multi-channel micro- and/or subwavelength-optical projection unit is analyzed via a statistical method and via a machine learning module,

wherein the machine learning module comprises a pre-trained artificial neural network,

wherein the machine learning module has been pre-trained with labelled training data, wherein the labelled training data comprises sample images generated by the predefined portion of a sample optical projection unit, and wherein the labelled training data comprises the at least one characteristic quantity corresponding to the respective sample images and/or the quality class of the respective sample projection unit, and

wherein the at least one characteristic quantity corresponding to the respective sample images is obtained by applying the statistical method to the sample images.

According to another aspect, the present disclosure refers to a test system for assessing the quality of a multi-channel micro- and/or subwavelength-optical projection unit, comprising an illumination unit, an image capturing device, an image analysis module and a control module, wherein the control module is configured to cause the test system to perform the method according to the previous aspect.

According to another aspect, the present disclosure refers to a computer program comprising instructions which, when the program is executed by a processing unit of the control module of the test system according to the previous aspects, cause the test system to carry out the steps of the method according to the previous aspects.

According to an example, the problem is solved by a method for assessing the quality of a multi-channel micro- and/or subwavelength-optical projection unit. The method comprises the following steps: At least a predefined portion of the micro- and/or subwavelength-optical projection unit is illuminated so that an image is generated by at least two channels of the predefined portion of the multi-channel micro- and/or subwavelength-optical projection unit. The image is captured and analyzed. At least one characteristic quantity is determined based on the analysis

of the image, wherein a value of the characteristic quantity is associated with at least one characteristic feature of the projection unit, at least one defect of the projection unit and/or at least one defect class of the projection unit. The quality of the projection unit is assessed based on the at least one characteristic quantity.

Subwavelength-optical elements, in particular subwavelength-lenses may also be called nano-optical elements, in particular nano-lenses.

The present disclosure is based on the finding that defects of the projection unit are directly linked to certain defects in the image generated by the projection unit. For example, deviations in the positions of optically active regions of the projection unit and deviations from a desired curvature of the individual optically active regions, and/or pinholes in the wafer each lead to respectively associated characteristic defects in the image.

Further, undesired pinholes in the projection unit cause bright circular spots in the image; unintentional misalignments during the manufacturing process lead to unsharp contours; Mechanical defects on lenses (e.g. scratches and/or cracks) lead to circular black rings and/or dark spots; undesired contaminations in the manufacturing process lead to dark freckles (dark spots), e.g. ununiformities in the pattern.

By analyzing the defects in the image generated by the projection unit, the quality of the projection unit can be assessed in a particularly fast and convenient fashion by applying image processing techniques to the captured image. From the state of the art, many different well-elaborated image processing techniques are known.

The image that is generated by at least the predefined portion of the projection unit, captured and subsequently analyzed may be the same image the projection unit will generate during its intended or parts thereof.

Alternatively or in addition, the image to be captured and analyzed may be generated by illuminating at least the predefined portion in the same way as during the intended use of the projection unit.

The projection unit is, for example, configured to create a projection of a motif on a surface, in particular a surface in a predefined arrangement with respect to the projection unit.

According to an example, the at least one characteristic quantity comprises at least one of sharpness, dark level, uniformity, brightness fluctuations and local defects. It has turned out that these quantities are especially suitable for assessing the quality of the projection unit, as they are directly associated with specific defects that may typically occur during the production of the projection unit.

According to a further example, the micro-optical projection unit is categorized into one of at least two quality classes based on the at least one characteristic quantity. Thus, the projection unit may be categorized into one of exactly two classes, e.g. “quality test passed” or “quality test not passed”. Alternatively, the projection unit may be categorized into one of several classes, such as “grade A”, “grade B”, etc. Each of the classes is associated with certain quality requirements that have to be met, particularly certain thresholds for one or several of the characteristic quantities that have to be met.

In a further example the projection unit comprises several micro- and/or subwavelength-optical elements, in particular micro-lenses and/or subwavelength-lenses, particularly wherein the optical elements have a size, a curvature, a masking and/or a position in the projection unit, the size, the curvature

and/or the position being at least one of the at least one characteristic feature of the projection unit. Deviations in the positions of the optical elements and/or deviations from a desired curvature of the individual optical elements are associated with specific defects in the captured image. By implication, defects in the captured image can be linked to defects of the projection unit and/or of the optical elements, such that the defects in the captured image can be used to assess the quality of the projection unit.

Generally speaking, each of the optical elements is configured to diffract, refract and/or guide light in a predetermined way. Thus, optical elements having diffracting, refracting and/or guiding properties can be implemented on the same projection unit, in particular on a common substrate.

At least some of the optical elements, particularly all optical elements may be established identically to one another. Likewise, at least some of the optical elements, particularly all optical elements may be established differently from one another, i.e. the optical elements may differ e.g. in size and/or curvature.

The projection unit may comprise at least one additional mechanical feature, e.g. a spacer and/or at least one protrusion. The spacer and/or the at least one protrusion may serve to set a distance between the projection unit and a respective further component during use of the projection unit.

Particularly, a geometric feature of the spacer and/or of the at least one protrusion may be a characteristic quantity of the projection unit. For example, a height, width and/or depth of the spacer and/or of the at least one protrusion may be a characteristic quantity of the projection unit.

Particularly, the optical elements form an array, the array having a distance between two neighboring optical elements being at least one of the at least one characteristic feature of the projection unit. The distance may be the minimal distance between the individual neighboring optical elements, the maximal distance between the individual neighboring optical elements and/or the average distance between the individual neighboring optical elements.

In another example, the quality of the projection unit is assessed during manufacturing of the projection unit, in particular end-of-line. Preferably, the quality assessment is repeated after several intermediate steps of

the manufacturing of the projection unit. Based on the assessment of the quality during the manufacturing, the projection unit may be discarded in an earlier stage of the manufacturing if necessary, thereby saving production time and production resources.

According to another example, manufacturing parameters, in particular at least one of the characteristic features, are adapted based on the quality assessment of the projection unit. Thus, the process parameters can be adapted such that the quality of the projection unit is enhanced. In other words, possible mistakes and/or deviations can be accounted for during the production, thereby attenuating the effect of these production deviations.

Manufacturing parameters that may be adapted are, for example, the baselayer thickness of the projection unit, the lens shape and/or the lens curvature.

Preferably, the image of projection unit is analyzed via a statistical method and/or via a machine learning module, in particular wherein the machine learning module comprises a pre-trained artificial neural network. In other words, the image may be analyzed with a purely classical, deterministic method that is based on classical algorithms, i.e. computational rules. On the other hand, the image may be analyzed solely via a machine learning method, or via a mixture of both.

The machine learning module may be pre-trained with labelled training data, wherein the labelled training data comprises sample images generated by the predefined portion of a sample optical projection unit, and wherein the labelled training data comprises the at least one characteristic quantity corresponding to the respective sample images and/or the quality class of the respective sample projection unit. Thus, the machine learning module is pre-trained in a supervised fashion.

Preferably, the machine learning module comprises an artificial neural network, for example a convolutional neural network (CNN) and/or a recurrent neural network (RNN) that is pre-trained to analyze the image, determine the at least one characteristic quantity and/or assess the quality of the projection unit.

Alternatively, the machine learning module may be pre-trained in a semi-supervised fashion with partially labelled data or in an unsupervised fashion.

According to a further example, the at least one characteristic quantity corresponding to the respective sample images is obtained by applying the statistical method to the sample images. Thus, the sample image is first analyzed via the classical statistical approach, wherein the result of the statistical analysis yields the label for the respective image.

In other words, the statistical approach is performed for a limited set of sample images. The sample images and the result of the statistical analysis form the training data for the machine learning module. Thus, the statistical method may only be applied to this limited training set in order to train the machine learning module, while the quality assessment during manufacturing of the projection unit is performed via the machine learning module.

According to the disclosure, the problem is further solved by a test system for assessing the quality of a multi-channel micro- and/or subwavelength-optical projection unit, comprising an illumination unit, an image capturing device, an image analysis module and a control module, wherein the control module is configured to cause the test system to perform the method described above. Regarding the advantages and features of the test system, reference is made to the explanations given above regarding the method, which also hold for the test system and vice versa.

According to an example, the test system comprises a device under test, particularly wherein the device under test is a multi-channel micro- and/or subwavelength-optical projection unit. Generally speaking, the device under test is a substrate, like a wafer comprising one or several multi-channel micro- and/or subwavelength-optical projection units. Particularly, the device under test may be established as a single projection unit.

According to the disclosure, the problem is further solved by a computer program comprising instructions which, when the program is executed by a processing unit of the control module of the test system described above, cause the test system to carry out the steps of the method described above. Regarding the advantages and features of the computer program, reference is made to the explanations given above regarding the method, which also hold for the computer program and vice versa.