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(54) **PROBE SENSOR WITH MULTI-DIMENSIONAL OPTICAL GRATING**

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G01B 11/14 (2006.01)

(52) **U.S. Cl.** **356/614**; 356/498

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See application file for complete search history.

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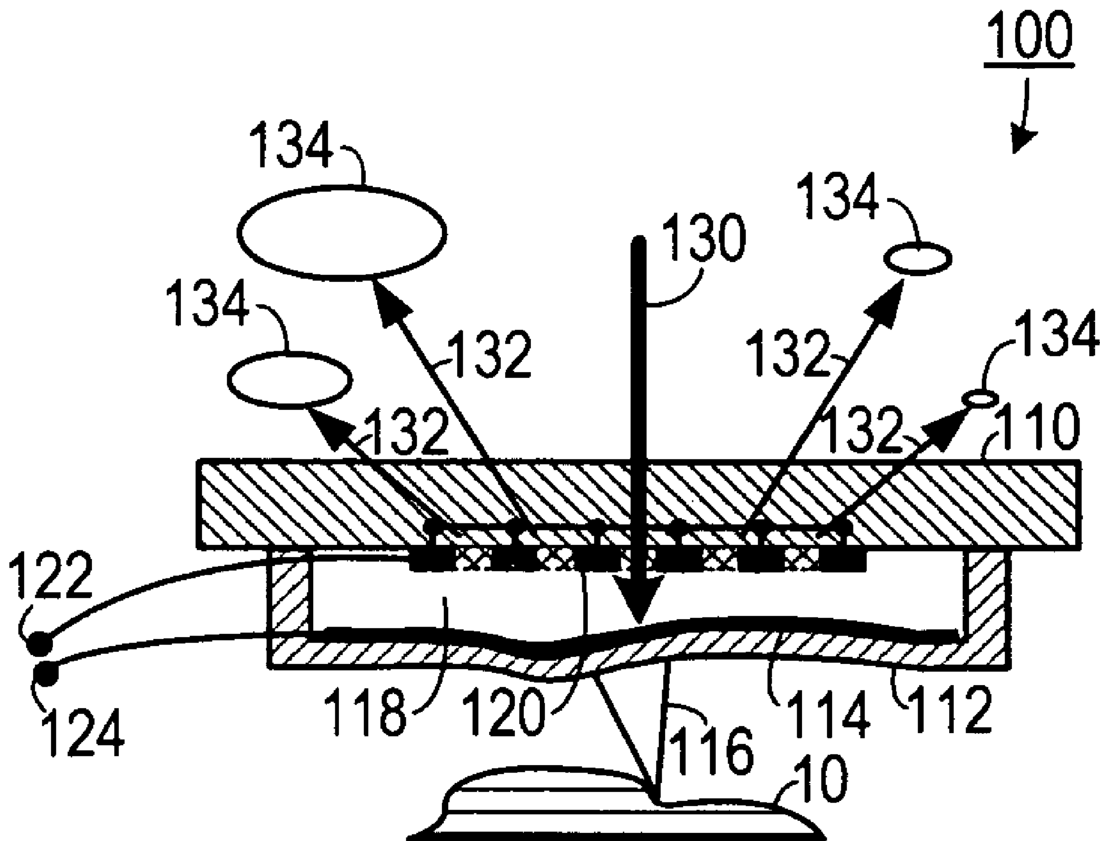
(57) **ABSTRACT**

A displacement sensor employs an electromagnetic radiation source that generates a beam of electromagnetic radiation for measuring a feature of an object. The displacement sensor includes a displacement probe, a multi-dimensional diffraction grating and a plurality of photon detectors. A reflection surface, which is changed when the probe interacts with the object, interacts with the beam from the electromagnetic radiation source and reflects a beam from the reflection surface. The multi-dimensional diffraction grating interacts with the reflected beam and generates a pattern of diffracted beams. Each photon detector senses a different diffracted beam, thereby providing information about the state of the probe.

25 Claims, 3 Drawing Sheets



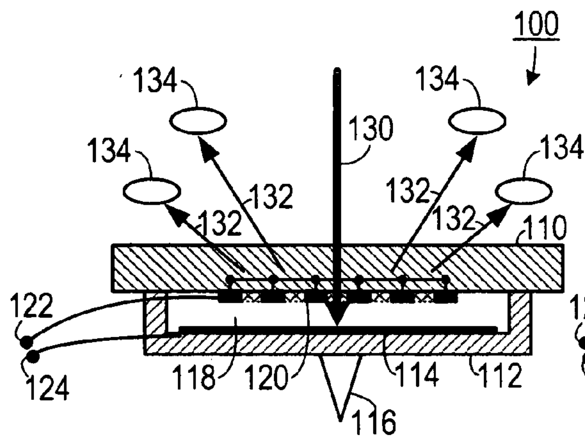


FIG. 1A

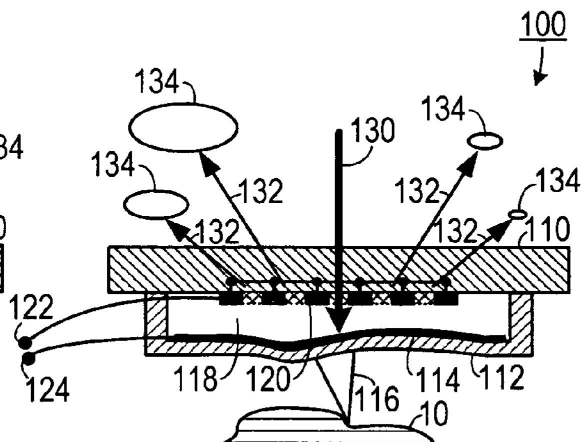


FIG. 1B

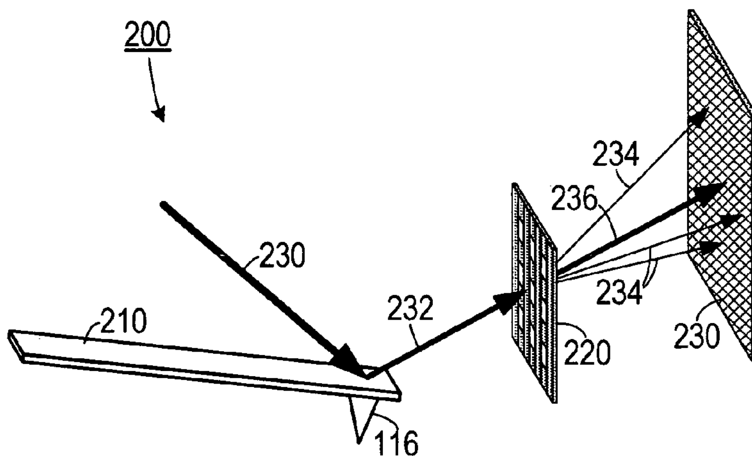


FIG. 2

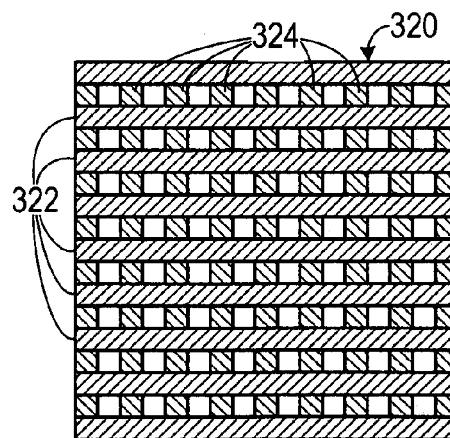


FIG. 3

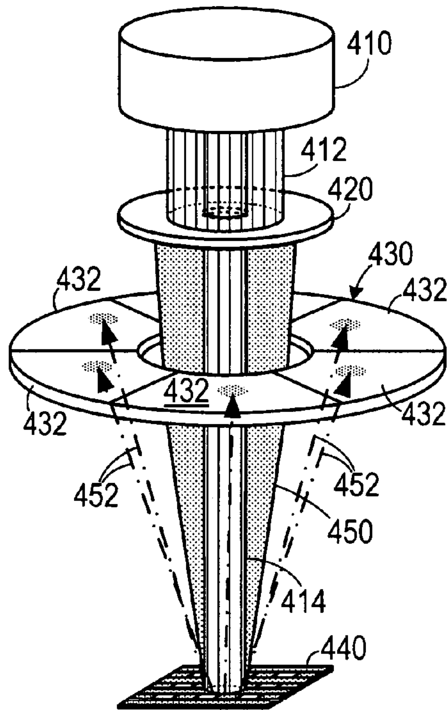


FIG. 4A

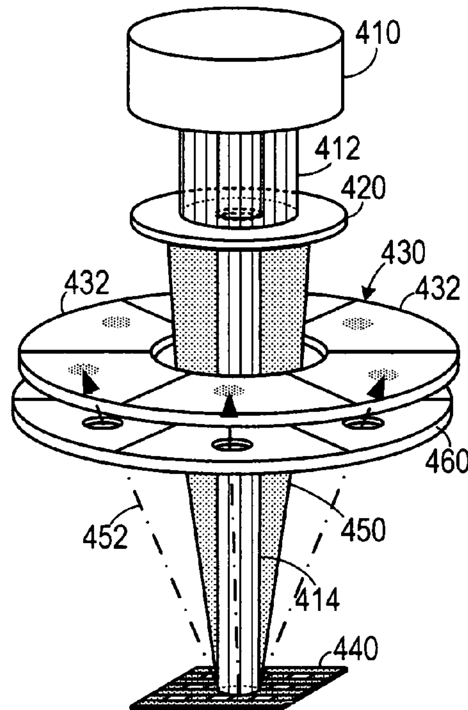


FIG. 4B

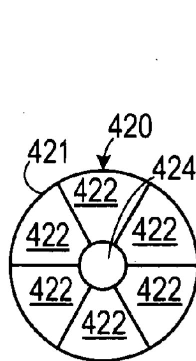


FIG. 4C

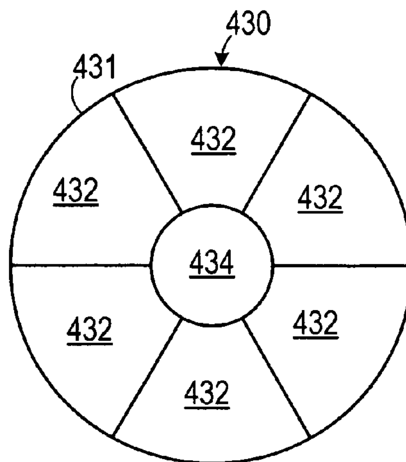


FIG. 4D

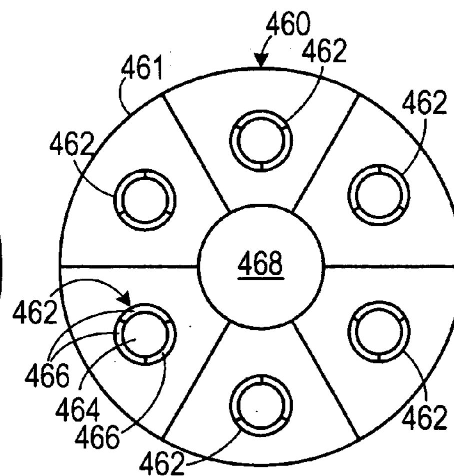


FIG. 4E

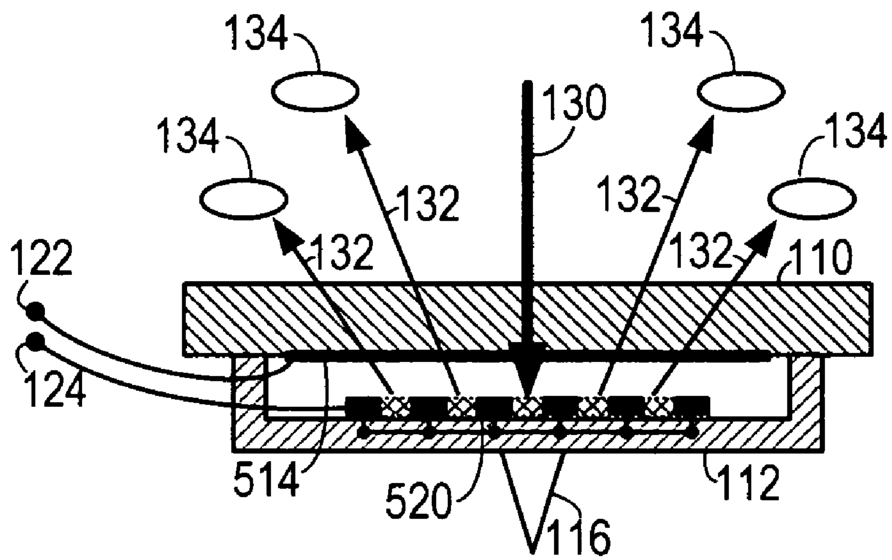


FIG. 5

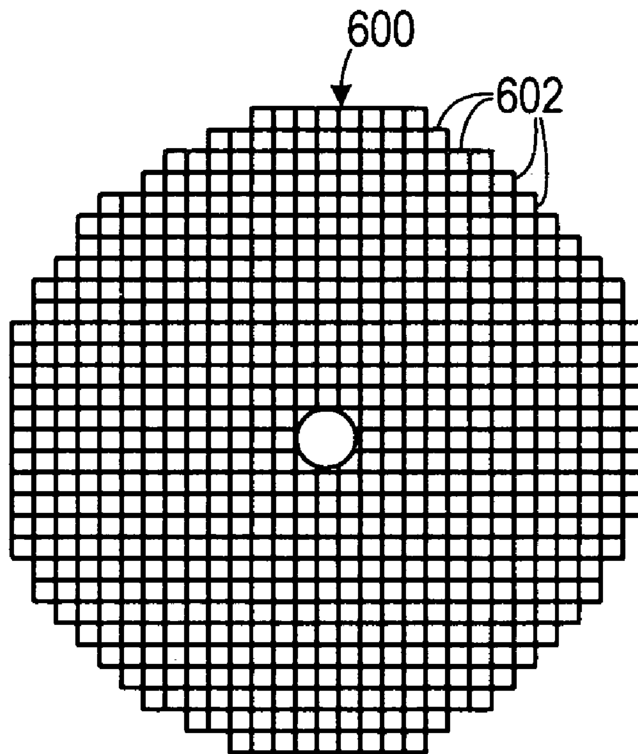


FIG. 6

PROBE SENSOR WITH MULTI-DIMENSIONAL OPTICAL GRATING

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to displacement sensors and, more specifically to a displacement sensor that uses a beam of electromagnetic radiation to measure displacement of a probe.

2. Description of the Prior Art

Atomic Force Microscopes (AFM) are used to measure surface characteristics of materials at the nano scale. AFM's are useful in measuring thin and thick film coatings, ceramics, composites, glasses, synthetic and biological membranes, metals, polymers, and semiconductors, among many other things. By using an AFM one can not only image the surface with near atomic resolution but can also measure the forces of the surface of a sample at the nano-Newton scale.

An AFM typically includes a probe with a probe tip extending therefrom. One type of probe is a cantilever; another is a force sensing integrated readout and active tip (FIRAT) probe. A cantilever includes a beam with a probe tip at a distal end. The beam may be angularly deflected to move the probe tip toward the object being measured. When the probe tip begins to interact with the object, the deflection of the beam can be measured by sensing light from a laser reflected off of the beam. A FIRAT probe includes a membrane that is supported by a frame. A FIRAT probe tip is typically affixed to the center of the membrane. The membrane may be displaced vertically by one of several methods. In one such method, the membrane has a first conductive surface that is spaced apart from a second conductive surface. When a similar charge is applied to both the first conductive surface and the second conductive surface, the two surfaces repel each other, thereby forcing the membrane (and the probe tip) away from the second conductive surface. The vertical displacement of the probe tip is controlled in this way. The vertical displacement of the membrane is detected by reflecting light from a laser off of the membrane and passing the reflected light through a diffraction grating and then measuring the intensity of one or more modes of the diffracted light using a photodetector.

A diffraction grating is a reflecting or transparent substrate whose surface contains fine parallel grooves or rulings that are equally spaced. When light is incident on a diffraction grating, diffractive and mutual interference effects occur, and light is reflected or transmitted in discrete directions, called orders. A diffraction grating includes a transparent surface with a plurality of parallel lines scored in the surface or printed on the surface and spaced apart at a distance so that they cause a beam of light at a predetermined wavelength to diffract. A one-dimensional diffraction grating includes one set of parallel lines, whereas a two-dimensional diffraction grating includes two sets of parallel lines transverse to each other. Certain natural substances and synthetic substances are diffraction gratings due to their ordering of unit cells in their molecular structures. For example, certain minerals act as diffraction gratings. Thus, certain crystals are diffraction gratings and, if they have greater than a nominal thickness, they are three-dimensional (or even multi-dimensional) diffraction gratings. A diffraction grating with more than one dimension will generate more than one diffracted beam, in which each beam can correspond to a different order. Also, a diffracted beam includes a "bright field" central portion and a "dark field" fringe portion. The central portion can provide information about one aspect of the surface from which the diffracted beam originates, whereas the fringe portion can provide information about another aspect of the surface.

Beam-deflection is the most common detection method used in modem commercial probe microscopes because of its simplicity and versatility. Typically, beam deflection requires a force-sensing structure, a probe tip, a light source, and a photon detector. The force sensing structure can be a cantilever, a membrane, or any other substrate that measures displacement or force. Displacement of the force-sensing structure is translated into angular displacement by reflecting light from the backside of the force-sensing structure onto a photon detector. Such displacement can be related to the force imparted onto the sample or to the probe tip.

One modification to the beam-deflection method is to insert a one-dimensional diffraction grating into the path of the beam and measure angular displacement of diffraction spots rather than angular displacement of the reflected incident beam. Recent advancements in probe microscopy have combined a micro-machined membrane, transparent substrate, electrostatic actuator and a diffraction grating for optical interferometric detection. Currently a one-dimensional diffraction grating is used in conjunction with a membrane for such applications. During operation, only one diffraction spot is detected and related to the displacement or force of the membrane tip. An inherent assumption in the current design is that the membrane deforms uniformly in the radial direction when actuated or placed under load. Therefore the membrane measures only vertical displacements or forces.

Existing systems can provide information about the vertical topography of a surface and the vertical component of surface forces exerted by the object on the probe tip. However, many surfaces also impart lateral and even twisting forces on the probe tip. This may result in non-vertical displacement and deformation of the surface (i.e., the membrane or the cantilever) to which the probe tip is attached. Information about these lateral and twisting forces clan provide valuable insight into the nature of a sampled surface. No existing system provides information about the degree or type of non-vertical displacement or deformation of the membrane or cantilever while it interacts with a surface.

Therefore, there is a need for a force microscopy system that provides information about non-vertical displacement and forces imparted on a probe tip by a sampled surface.

There is also a need for a microscopy system that provides information through both bright field analysis and dark field analysis of a diffracted beam.

SUMMARY OF THE INVENTION

The disadvantages of the prior art are overcome by the present invention which, in one aspect, is a displacement sensor that employs an electromagnetic radiation source that generates a beam of electromagnetic radiation for measuring a feature of an object. The displacement sensor includes a displacement probe, a multi-dimensional diffraction grating and a plurality of photon detectors. The displacement probe has a first surface from which a probe depends outwardly. An oppositely-disposed reflection surface is changed when the probe interacts with the object. The reflection surface is disposed so as to interact with the beam from the electromagnetic radiation source and so that a reflected beam reflects from the reflection surface. A characteristic of the reflected beam is indicative of a state of the probe. The multi-dimensional diffraction grating is disposed so as to interact with the reflected beam and generate a pattern of diffracted beams.

Each of the plurality of photon detectors is disposed so as to sense a different one of the diffracted beams, thereby providing information about the state of the probe.

In another aspect, the invention is a displacement sensor that includes a displacement probe, a two-dimensional diffraction grating, a light source, a first annular photon detector and a second annular photon detector. The displacement probe has a first surface, a probe depending outwardly therefrom, and an oppositely-disposed reflection surface that is changed when the probe interacts with the object. The reflection surface is disposed so as to interact with the beam from the light source and so that a reflected beam reflects from the reflection surface. A characteristic of the reflected beam is indicative of a state of the probe. The two-dimensional diffraction grating is disposed between the light source and the reflection surface so that at least one diffracted beam is created by the diffraction grating. The light source generates a beam of light that is directed to the reflection surface. The first annular photon detector is disposed between the light source and the diffraction grating and defines a first hole passing therethrough. The first hole has a diameter corresponding to a diameter of a light beam directed to the reflection surface. The first annular photon detector includes a plurality of spaced-apart first photosensitive segments, each of which is responsive to a quality of the reflected beam. The second annular photon detector is disposed between the first annular photon detector and the diffraction grating. The second annular photon detector defines a second hole passing therethrough. The second hole has a diameter sufficient to allow the reflected beam to pass therethrough. The second annular photon detector includes a plurality of spaced-apart second photosensitive segments, each of which is responsive to a quality of the diffracted beam.

In another aspect, the invention is a displacement sensor, employing an electromagnetic radiation source that generates a beam of electromagnetic radiation, for measuring a feature of an object. The displacement sensor includes a displacement probe, a multi-dimensional diffraction grating, a first photon detector and a second photon detector. The displacement probe has a first surface with a probe depending outwardly therefrom. An oppositely-disposed reflection surface is changed when the probe interacts with the object. The reflection surface is disposed so as to interact with the beam from the electromagnetic radiation source and so that a reflected beam reflects from the reflection surface. A characteristic of the reflected beam is indicative of a state of the probe. The multi-dimensional diffraction grating is disposed so as to interact with the reflected beam and generate at least one diffracted beam. The first photon detector is spaced apart from the diffraction grating and is disposed so as to sense a central portion of the diffracted beam. The second photon detector is spaced apart from the diffraction grating and is spaced apart from the first photon detector. The second photon detector is disposed so as to sense a fringe portion of the diffracted beam.

In yet another aspect, the invention is a method of measuring displacement of a probe having a reflective surface and a light source that generates a beam of light directed to the reflective surface in which a reflected beam is reflected from the reflective surface. In the method, the reflected beam is diffracted with a multi-dimensional diffraction grating. A quality of at least one diffracted beam propagated from the diffraction grating, indicative of a state of the probe, is measured.

These and other aspects of the invention will become apparent from the following description of the preferred embodiments taken in conjunction with the following drawings. As would be obvious to one skilled in the art, many variations and modifications of the invention may be effected without departing from the spirit and scope of the novel concepts of the disclosure.

BRIEF DESCRIPTION OF THE FIGURES OF THE DRAWINGS

FIG. **1**A is a cross sectional view of one illustrative FIRAT embodiment of the invention.

FIG. **1**B is a cross sectional view showing the embodiment shown in FIG. **1**A in which the probe is laterally deflected by a sample.

FIG. **2** is a perspective view of a cantilever embodiment of the invention.

FIG. **3** is a plan view of a two-dimensional diffraction grating.

FIG. **4**A is a top perspective view of one illustrative embodiment of the invention.

FIG. **4**B is a top perspective view of an illustrative embodiment that performs both bright field analysis and dark field analysis on the diffraction spots.

FIG. **4**C is a plan view of an annular disk used to measure properties of the reflected beam.

FIG. **4**D is a plan view of an annular disk used to measure properties of a diffracted beam pattern.

FIG. **4**E is a plan view of an annular disk used to measure properties of fringe portions of a diffracted beam pattern.

FIG. **5** is a cross sectional view of an embodiment in which the diffraction grating is disposed against a membrane in a FIRAT probe.

FIG. **6** is a plan view of a charge coupled device array photon detector.

DETAILED DESCRIPTION OF THE INVENTION

A preferred embodiment of the invention is now described in detail. Referring to the drawings, like numbers indicate like parts throughout the views. Unless otherwise the figures are not drawn to scale and objects may be shown out of proportion to other objects for the sake of clarity. As used in the description herein and throughout the claims, the following terms take the meanings explicitly associated herein, unless the context clearly dictates otherwise: the meaning of “a,” “an,” and “the” includes plural reference, the meaning of “in” includes “in” and “on.”

As shown in FIGS. **1**A and **1**B, one illustrative embodiment of the invention is a FIRAT-type displacement sensor that includes a substrate **110** and a spaced-apart displacement structure, such as membrane **112**, forming a cavity **118** there between. A two-dimensional diffraction grating **120** is disposed on the cavity-side of the substrate **110** and a reflective electrode **114** is disposed on the cavity-side of the membrane **112**. The membrane **112** may be biased by applying a charge to the diffraction grating **120** and the electrode **114** through contacts **122** and **124**, respectively. A probe tip **116** extends downwardly from-the membrane **112**.

A light beam **130** is directed toward the reflective electrode **114** and reflects therefrom. When the reflected beam (not shown expressly in this figure) passes through the diffraction grating **120** a plurality of diffracted beams **132** are generated. The diffracted beams **132** can be detected by suitably-placed photon detectors **134**.

As shown in FIG. **1**B, when the membrane **112** is biased toward a surface **10** of an object, the probe tip **116** may interact with the surface **10** and cause the membrane **112** to deform. This deformation causes the diffracted beams **132** to change in at least one measure of quality with respect to each other. For example, the intensity of the diffracted beams **132** can change relative to each other. Other quality measures could include angular displacement and phase angle. The relative change in quality is represented by the relative sizes of the photon detectors **134** shown in FIG. **1**B.

A cantilever-type displacement sensor **200** embodiment of the invention is shown in FIG. **2**. This displacement sensor **200** includes a cantilever beam **210** with a probe tip **116** depending downwardly therefrom. An incident light beam **230** is reflected off of a surface of the cantilever beam **210**, forming a reflected light beam **232**. A two-dimensional diffraction grating **220** is placed ion the path of the reflected light beam **232**, thereby forming a plurality of diffraction beams **234**, along with a remnant **236** of the reflected beam **232**. The diffraction beams **234** and the remnant beam **236** are sensed with a photon sensor **230**.

A two-dimensional diffraction grating **320**, shown in FIG. **3**, includes a first set of parallel lines **322** and a second set of parallel lines **324** that is transverse to the first set of parallel lines **322**. (It should be noted that the lines are not drawn to scale, nor are they necessarily drawn proportionally in width to the width of the spaces between them.) While the sets of lines are shown at right angles to each other, other angles could be used in specific applications.

One probe sensor (that could be used, for example, with a FIRAT-type probe), shown in FIG. **4**A, includes a light source **410** that generates a light beam **412** of a predetermined wavelength and a diffraction grating **440**, which generates a pattern of diffracted beams **452**. The diffraction grating **440** may be placed against the substrate of the probe (which is not shown in this figure, but is shown in FIGS. **1**A and **1**B). A reflected beam photon detector **420** (shown in detail in FIG. **4**C) includes a first annular disk **421** and a plurality of spaced-apart photon detector segments **422**. The annular disk **420** defines a centrally-disposed hole **424** passing therethrough. The centrally-disposed hole **424** has a diameter that allows a portion **414** of the light beam **412** to pass therethrough. The configuration shown can measure the displacement and the spatial intensity distribution of the reflected beam **450**. Other qualities of the beams (e.g., position and phase) may be measured with different configurations and through the use of signal processing methods.

A diffracted beam photon detector **430** (shown in detail in FIG. **4**D) is placed between the reflected beam photon detector **420** and the diffraction grating **440**. The diffracted beam photon detector **430** includes an annular disk **431** that defines a central hole **434**, through which the reflected beam **450** passes, and includes a plurality of diffracted beam photon detector segments **432**.

The embodiment shown in FIG. **4**A can be modified according to FIG. **4**B by adding a dark field photon detector **460** between the diffraction grating **440** and the diffracted beam photon detector **430**. In this configuration, the diffracted beam photon detector **430** acts as a bright field photon detector that detects the central portion of the diffracted beams **452**, whereas the dark field photon detector **460** detects a fringe portion of each of the diffracted beams **452**. The dark field photon detector **460** (shown in detail in FIG. **4**E) includes an annular disk **461**, defining a hole **468** for allowing the reflected beam **450** to pass therethrough, and a plurality of spaced-apart fringe photon detectors **462**. The fringe photon detectors **462** may include spaced-apart photon detector segments **466**, which detect the relative intensity of different portions of the fringe portion of the diffracted beams, spaced around a hole **464**. The hole **464** is sized to allow the central portion of the diffracted beam to pass therethrough.

High resolution probe microscopy is not only limited by the sharpness of the probe tip but also by the data acquisition and processing techniques. The displacement and force can be measured through relative changes in location of individual diffractions spots. To isolate the amplitude and phase components of the deflection and force data, it is necessary to isolate discrete regions of individual diffraction spots. For example, the central portion and fringes of a diffraction spot are directly related to the amplitude and phase components of the data, respectfully.

In one embodiment, as shown in FIG. **5**, the diffraction grating **520** could be coincidental with reflective surface **114**. In this embodiment, an electrode **514** could be added for the purpose of biasing and deflecting the membrane **112**.

The photon detectors could include any of the many different types of photon detectors known in the art. For example, complementary metal oxide semiconductor (CMOS) photon detectors could be used. As shown in FIG. **6**, an array **600** of charge coupled devices (CCDS) **602** could provide highly precise analysis of both the reflected and diffracted beams.

By diffracting the beam and looking at the zero-order Laue zone, first-order Laue zone, second-order Laue zone, higher order Laue zones and any combination thereof, it is possible to extract more accurately the position, shape and forces detected by the probe in the vertical and lateral directions. The devices disclosed herein can be expanded not only to measure vertical displacements and forces acting on the probe tip, but also measure non-uniformity within the membrane and relate such deformation to lateral displacements and forces on the probe tip. In addition, the quality of the membrane can be fully characterized during operation, thereby improving precision of measurements. If the incident beam is analyzed, the resultant image is acquired using bright-field analysis, and if any individual or combinations of diffracted spots are analyzed, the resultant image is acquired using dark-field analysis. In order to measure vertical and lateral displacement forces of a cantilever, membrane or any other force-sensing structure, it is useful to gather discrete information from both the reflected beam and the diffracted beams simultaneously.

While the embodiments above discuss a light beam to detect displacement, it is understood that electromagnetic beams of many frequencies (including many non-visible frequencies) could be employed with the invention. It is intended that electromagnetic beams of all such frequencies fall within the scope of the claims. Also, while cantilever and membrane embodiments are disclosed herein, it is understood that many other displacement or force sensing structures may be used with the invention.

The above described embodiments, while including the preferred embodiment and the best mode of the invention known to the inventor at the time of filing, are given as illustrative examples only. It will be readily appreciated that many deviations may be made from the specific embodiments disclosed in this specification without departing from the spirit and scope of the invention. Accordingly, the scope of the invention is to be determined by the claims below rather than being limited to the specifically described embodiments above.

What is claimed is:

1. A displacement sensor, employing an electromagnetic radiation source that generates a beam of electromagnetic radiation, for measuring a feature of an object, comprising:

a. a displacement structure having a first surface, a probe depending outwardly therefrom, and an oppositely-disposed reflection surface that is changed when the probe interacts with the object, the reflection surface disposed so as to interact with the beam from the electromagnetic radiation source and so that a reflected beam reflects from the reflection surface, a characteristic of the reflected beam indicative of a state of the probe;

b. a multi-dimensional diffraction grating disposed so as to interact with the reflected beam and generate a pattern of diffracted beams; and

c. a first photon detector that is configured to detect an intensity of the reflected beam; and

d. at least a second photon detector that is configured to detect an intensity of a diffracted beam that is diffracted from the multi-dimensional diffraction grating,

wherein the intensity of the reflected beam and the intensity of the diffracted beam are indicative of both a vertical displacement of the probe and a lateral displacement of the probe.

2. The displacement sensor of claim **1**, wherein the multi-dimensional diffraction grating comprises a two-dimensional diffraction grating.

3. The displacement sensor of claim **1**, wherein the multi-dimensional diffraction grating comprises a three-dimensional diffraction grating.

4. The displacement sensor of claim **1**, wherein the multi-dimensional diffraction grating is disposed adjacent to the reflection surface.

5. The displacement sensor of claim **1**, wherein the multi-dimensional diffraction grating is spaced apart from the reflection surface.

6. The displacement sensor of claim **1**, wherein the reflection surface comprises a reflective surface.

7. The displacement sensor of claim **1**, wherein the plurality of photon detectors comprises:

a. a reflected beam photon detector; and

b. a plurality of diffracted beam photon detectors.

8. The displacement sensor of claim **7**, wherein the reflected beam photon detector comprises a plurality of spaced-apart photon detector segments.

9. The displacement sensor of claim **7**, wherein the reflected beam photon detector comprises an annular disk defining a centrally-disposed hole passing therethrough, the centrally-disposed hole having a diameter sufficient to allow a portion of the beam of electromagnetic radiation, of predetermined intensity, to pass therethrough toward the reflection surface.

10. The displacement sensor of claim **7**, wherein each of the diffracted beam photon detectors comprises a plurality of spaced-apart photon detector segments.

11. The displacement sensor of claim **10**, wherein each of the spaced-apart photon detector segments comprises:

a. a bright field photon detector disposed so as to interact with a central portion of a diffracted beam; and

b. a dark field photon detector disposed so as to interact with a fringe portion of the diffracted beam.

12. The displacement sensor of claim **11**, wherein the bright field photon detector comprises an annular disk defining a centrally-disposed hole passing therethrough, the centrally-disposed hole having a diameter sufficient to allow the central portion of the diffracted beam, to pass therethrough toward the bright field photon detector.

13. The displacement sensor of claim **12**, the disk being divided into a plurality of spaced-apart photosensitive segments.

14. The displacement sensor of claim **1**, wherein the plurality of photon detectors comprises an array of charge coupled devices.

15. The displacement sensor of claim **1**, wherein the plurality of photon detectors comprises a plurality of complementary metal oxide image sensors.

16. A displacement sensor, employing an electromagnetic radiation source that generates a beam of electromagnetic radiation, for measuring a feature of an object, comprising:

a. a displacement structure having a first surface, a probe depending outwardly therefrom, and an oppositely-disposed reflection surface that is changed when the probe interacts with the object, the reflection surface disposed so as to interact with the beam from the electromagnetic radiation source and so that a reflected beam reflects from the reflection surface, a characteristic of the reflected beam indicative of a state of the probe;

b. a multi-dimensional diffraction grating disposed so as to interact with the reflected beam and generate at least one diffracted beam;

c. a first photon detector, spaced apart from the diffraction grating, that is disposed so as to sense a central portion of the diffracted beam and that is configured to detect an intensity of the reflected beam; and

d. a second photon detector, spaced apart from the diffraction grating and spaced apart from the first photon detector, that is disposed so as to sense a fringe portion of the diffracted beam and that is configured to detect an intensity of a diffracted beam that is diffracted from the multi-dimensional diffraction grating,

wherein the intensity of the reflected beam and the intensity of the diffracted beam are indicative of both a vertical displacement of the probe and a lateral displacement of the probe.

17. A method of measuring displacement of a probe having a reflective surface and a light source that generates a beam of light directed to the reflective surface in which a reflected beam is reflected from the reflective surface, comprising the steps of:

a. placing the probe against an object;

b. diffracting the reflected beam with a multi-dimensional diffraction grating;

c. measuring the reflected beam with a first photon detector that is configured to detect an intensity of the reflected beam; and

d. measuring a quality of at least one diffracted beam propagated from the diffraction grating with at least a second photon detector that is configured to detect an intensity of a diffracted beam that is diffracted from the multi-dimensional diffraction grating, the quality indicative of a state of the probe

wherein the intensity of the reflected beam and the intensity of the diffracted beam are indicative of both a vertical displacement of the probe and a lateral displacement of the probe.

18. The method of claim **17**, wherein the step of diffracting the reflected beam with a multi-dimensional diffraction grating comprises diffracting the reflected beam with a two-dimensional diffraction grating.

19. The method of claim **17**, wherein the step of measuring a quality of at least one diffracted beam comprises measuring an intensity quality of the diffracted beam.

20. The method of claim **19**, wherein the step of measuring a quality of at least one diffracted beam comprises the step of measuring a quality of a central portion of the diffracted beam.

21. The method of claim **19**, wherein the step of measuring a quality of at least one diffracted beam comprises the step of measuring a quality of a fringe portion of the diffracted beam.

22. The method of claim **19**, wherein the step of measuring a quality of at least one diffracted beam comprises measuring a positional quality of the diffracted beam.

23. The method of claim **19**, further comprising the step of measuring a quality of the reflected beam.

24. The method of claim **23**, wherein the step of measuring a quality of the reflected beam comprises measuring an intensity quality of the reflected beam.

25. The method of claim **23**, wherein the step of measuring a quality of the reflected beam comprises measuring a positional quality of the reflected beam.

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