

United States Patent [19]

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Aksyuk et al.

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[54] **MICROMECHANICAL XYZ STAGE FOR USE WITH OPTICAL ELEMENTS**

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[51] **Int. Cl.**⁶ **G02B 21/26; H02N 1/00**

[52] **U.S. Cl.** **359/392; 359/393; 310/309**

[58] **Field of Search** 354/391, 392, 354/393; 248/913; 310/309

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[57] **ABSTRACT**

A micromachined xyz stage, and microscopes utilizing such a stage, are disclosed. The xyz stage includes co-planar x- and y-drive means linked to a sample stage. Such x- and y-drive means are operable to position the sample stage in an x-y plane. The xyz stage further includes z-drive operable to move the sample stage out of the x-y plane. The z-drive can be implemented by suspending a flat-plate electrode over the sample stage using hinged plate supports. As a voltage is applied across the plate electrode and the sample stage, an electrostatic force is generated, causing the sample stage to move towards the plate electrode. The hinged plate supports facilitate assembly of the z-drive, in addition to providing support for it in its assembled configuration. By incorporating an optical fiber, the aperture of which has been drawn down to submicron size, a near-field scanning optical microscope can be formed. By forming a micromachined tip on the xyz stage, a scanning tunneling microscope or an atomic force microscope can be formed.

17 Claims, 4 Drawing Sheets

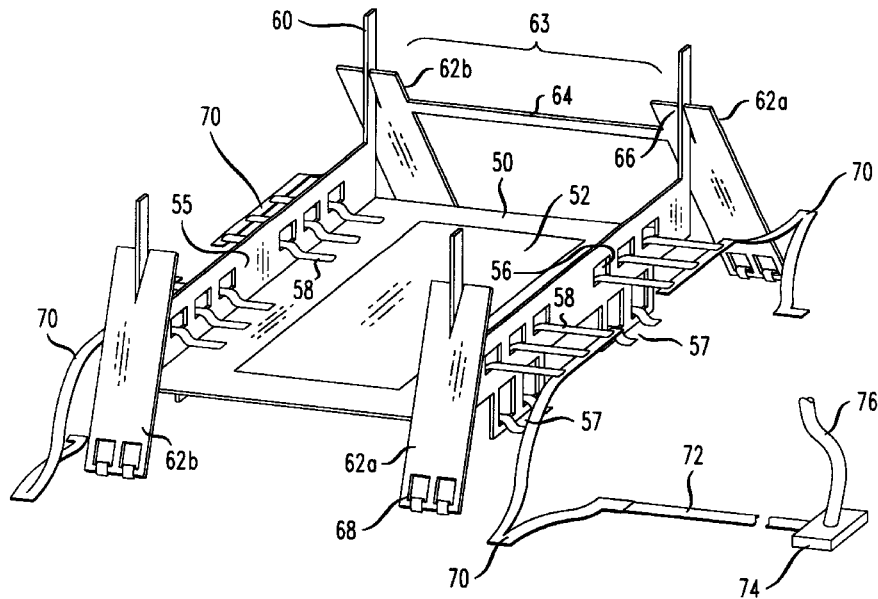


FIG. 1

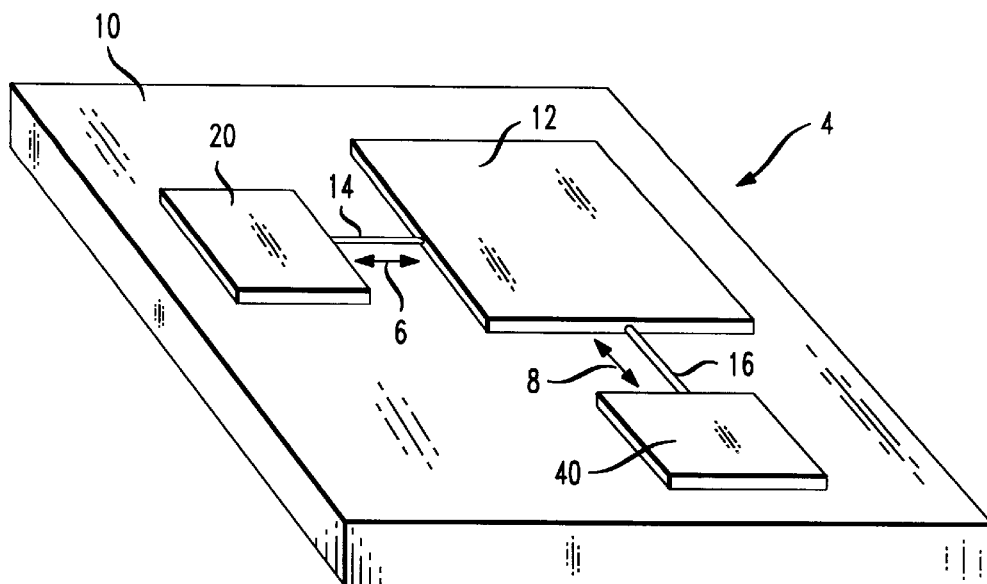


FIG. 2

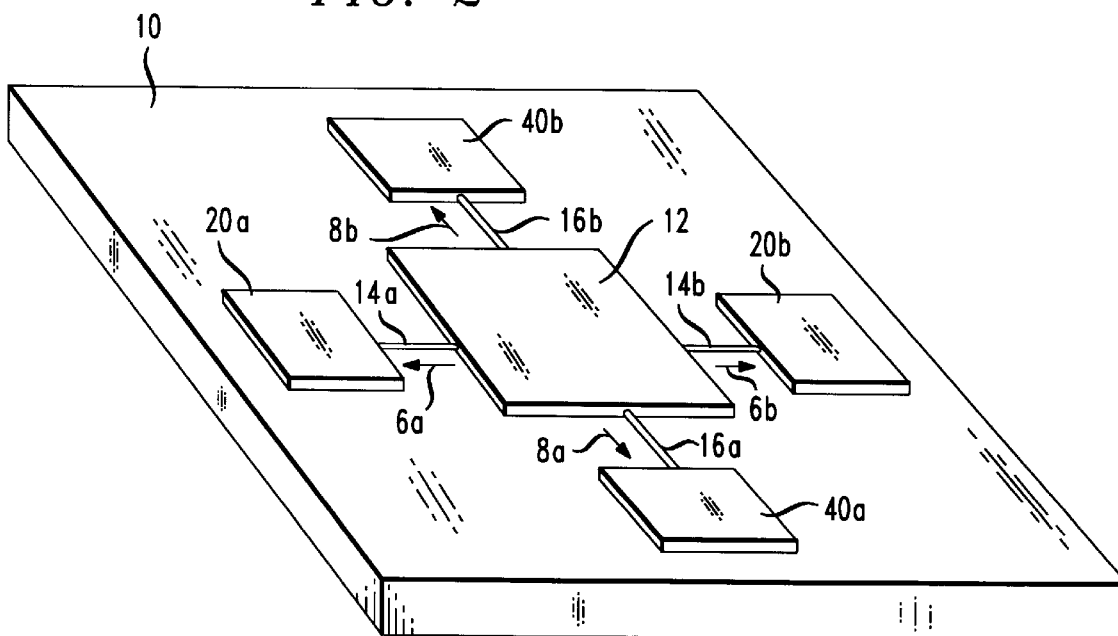


FIG. 3

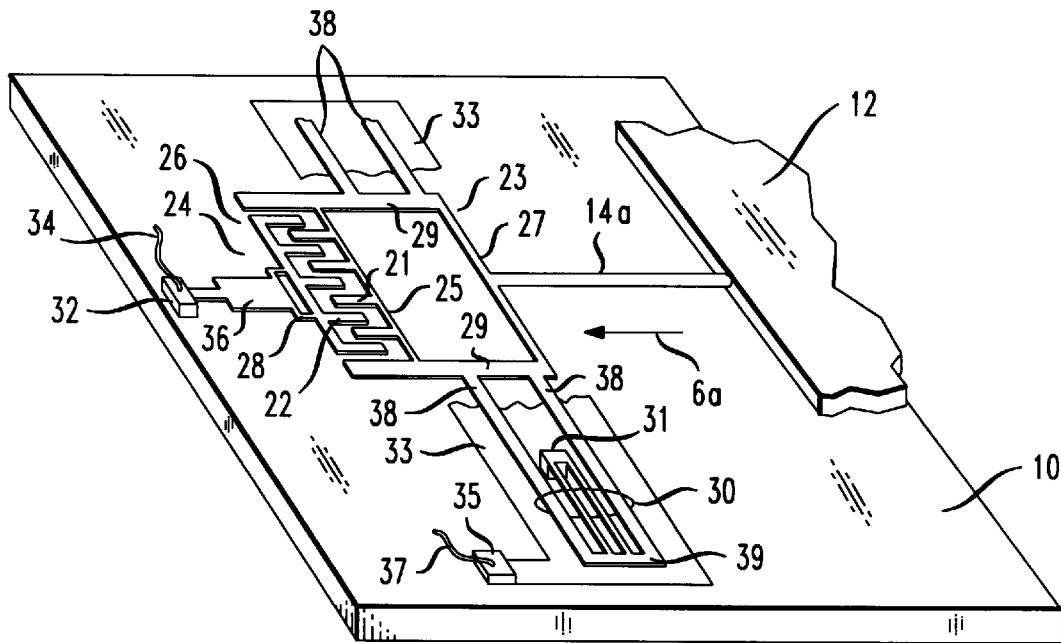


FIG. 4

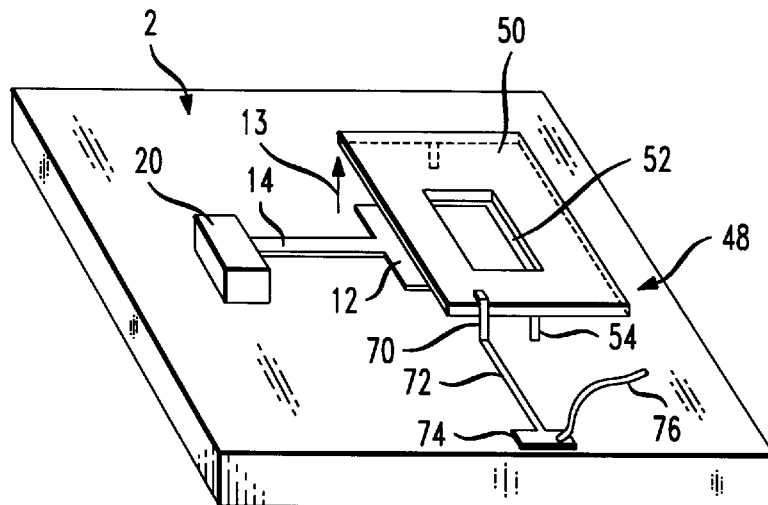


FIG. 5

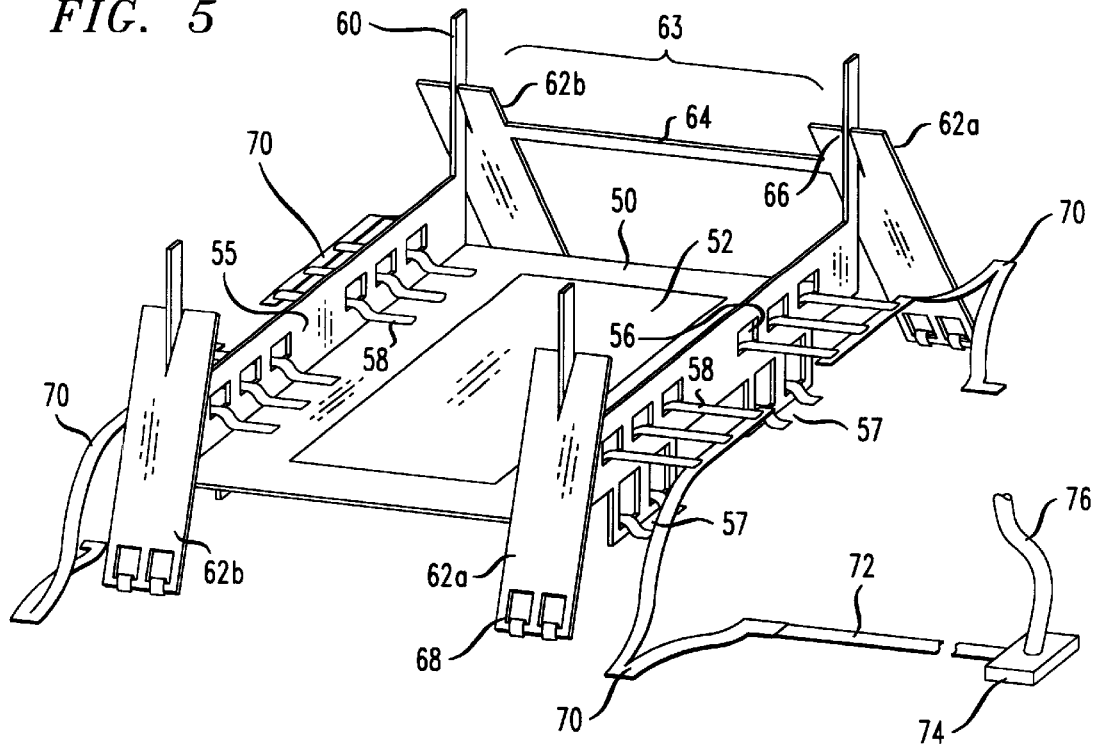


FIG. 6

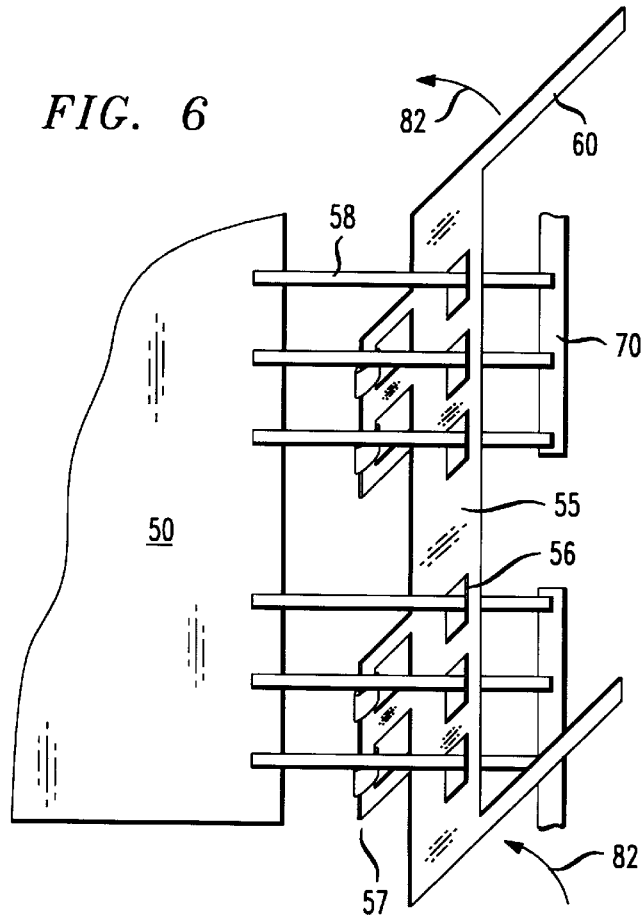


FIG. 7

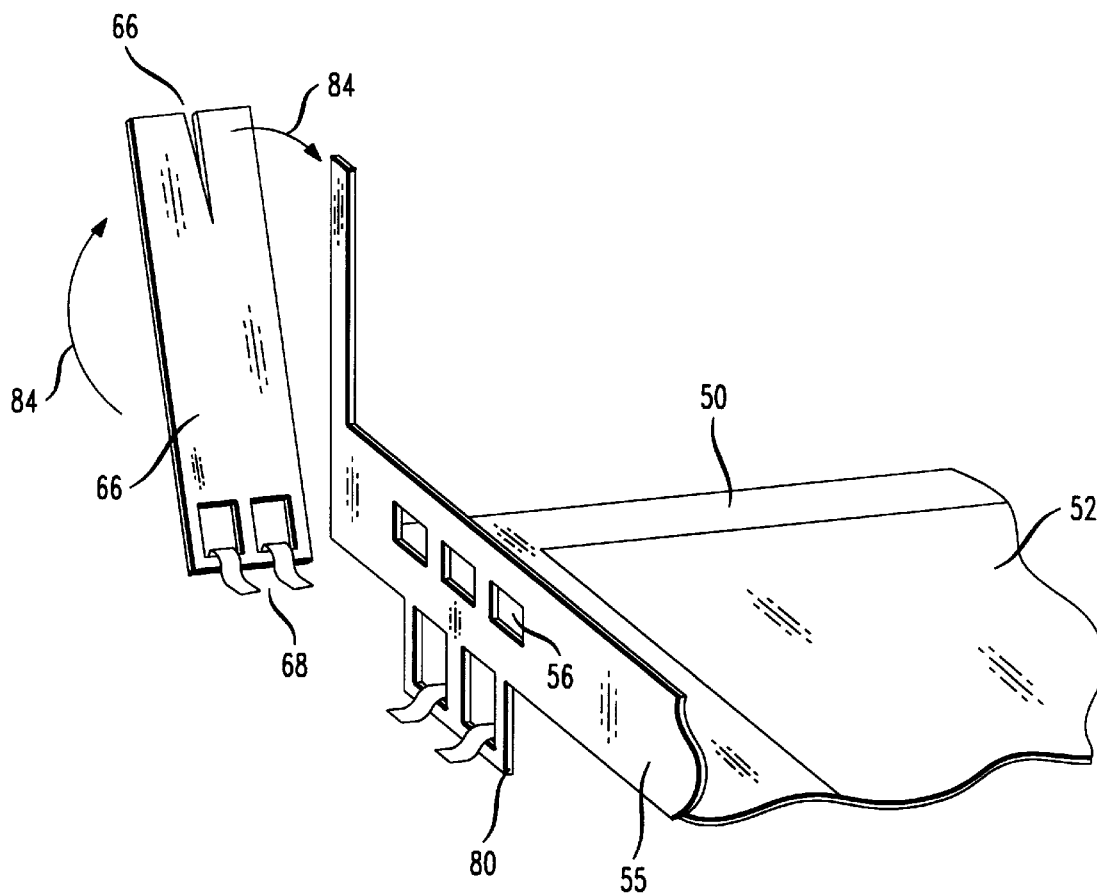
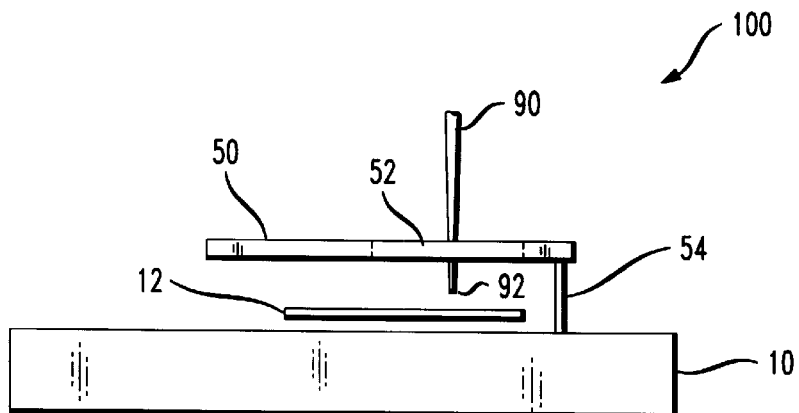


FIG. 8



1

MICROMECHANICAL XYZ STAGE FOR USE WITH OPTICAL ELEMENTS

FIELD OF THE INVENTION

The present invention relates to an xyz stage for micro-aligning an article placed thereon and its use in conjunction with optical elements.

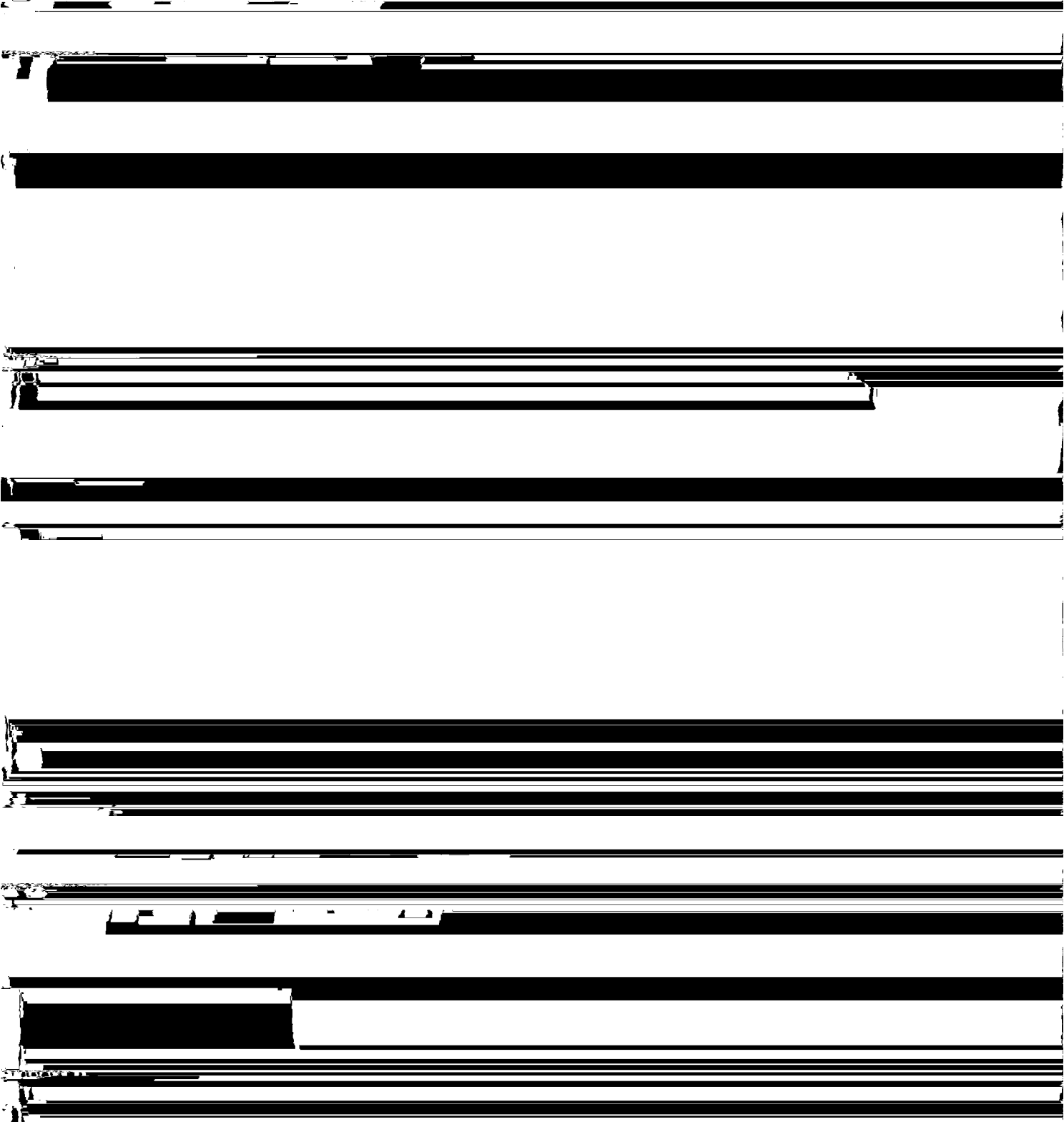
BACKGROUND OF THE INVENTION

Near-field scanning optical microscopes (NSOMs) having submicron spatial resolution are physically large and expen-

2

electrode. The support means can be rotatable hinged plates. Such rotatable hinged plates facilitate assembly of the z-drive means, in addition to providing support for it in its assembled configuration. The z-drive means is physically adapted for allow access to the sample stage.

The present xyz stage may be advantageously used in conjunction with optical elements. For example, in one embodiment, the xyz stage is used to form a NSOM. According to the invention, the z-drive means receives the tip of an optical fiber that has be drawn down to submicron size. The optical fiber delivers light to a sample disposed on the sample stage beneath the z-drive means. The stage is



push, or, more preferably, to pull. Thus, drive actuator **20a** is operable to apply a force to the sample plate **12**, via the linkage **14a**, so that the sample plate moves toward the drive actuator **20a** as indicated by the direction vector **6a**. Similarly, drive actuators **20b**, **40a** and **40b** are operable, when actuated, to move the sample plate **12** in the direction indicated by respective direction vectors **6b**, **8a** and **8b**.

In one embodiment, the drive actuators **20a**, **20b**, **40a**, **40b** are configured as conventional "comb" drives. The comb drive **20a** is illustrated in FIG. 3. All four comb drives are identical; it is the placement of the comb drive that determines the direction in which it moves the sample plate **12** upon actuation.

As shown in FIG. 3, the comb drive **20a** comprises interdigitated movable teeth members **21** and fixed teeth members **22**. The movable teeth members **21** depend from a first portion **25** of stage **23**. The linkage **14a** depends from a second portion **27** of the stage **23**. Fixed teeth members **22** depend from a first portion **26** of a frame **24**. A second portion **28** of the frame **24** is disposed on wire trace **36**. Wire trace **36** is in electrical contact with bond pad **32** which receives a wire **34** for delivering a voltage to the fixed teeth **22** of the comb drive **20a**.

Arms **38** of drive supports **30** (only one drive support is shown in its entirety for clarity) are attached to the stage **23** at stage side members **29**. The drive supports **30** support the stage **23**, and depending movable teeth members **21** and linkage **14a**, above underlying layers, e.g., the support surface **10** or any conductive layers or insulating layers disposed thereon. The drive supports **30** elevate the stage **23**, linkage **14a** and movable teeth members **21** about 2 microns above such underlying surfaces. A conductive layer **33**, typically polysilicon, is disposed on the support surface **10** beneath the drive supports **30**, the stage **23**, the movable teeth members **21**, etc. The drive support **30** is in electrical contact with, and fixed to, the conductive layer **33**, at riser member **31**. The conductive layer **33** is in electrical contact with a wire bond pad **35** that receives a wire **37** for delivering a voltage to the stage **23** and, thereby, to the movable teeth members **21**.

In operation, a voltage is placed across the interdigitated teeth members **21** and **22** generating an electrostatic force therebetween. In response, the movable teeth members **21** are pulled towards the fixed teeth members **22** as indicated by the direction vector **6a**. Since the sample plate **12** is connected to the movable teeth members **21** via the stage **23** and linkage **14a**, the sample plate is moved in the direction indicated by the direction vector **6a**, as well.

The other three comb drives **20b**, **40a**, **40b** are identically constructed and operable to pull the sample plate **12** in the direction indicated by the respective direction vectors **6b**, **8a** and **8b** shown in FIG. 2. The xy stage **4** described above and illustrated in FIGS. 1-2 is known in the prior art. The x- and y- drive means **20**, **40** may be implemented using a variety of suitably-configured actuators known to those skilled in the art. The comb drives described above are one of many suitable embodiments of such an actuator.

In the exemplary embodiment shown in FIG. 3, the drive support **30** is "folded" at the member **39**, i.e., the arms **38** project from the member **39** in a direction 180° opposed to the direction in which arms project from the anchor member **31**. That arrangement is referred to as a "folded beam" configuration. It should be appreciated that in other embodiments, the drive supports may be configured differently, as is within the capabilities of those having ordinary skill in the art, yet still provide support for, and, optionally, electrical contact with, drive members.

An xyz stage **2** is formed by adding a z-drive means to the aforescribed xy stage **4**. According to the present invention, the z-drive means is suitably configured for generating an electrostatic force that moves the sample stage **12** out of the x-y plane. In an exemplary embodiment illustrated in FIG. 4, z-drive means **48** comprises a parallel-plate actuator and support means **54**. For clarity of presentation, the y-drive means **40** is omitted from FIG. 4.

In the embodiment shown in FIG. 4, the parallel-plate actuator is realized by suspending a plate electrode **50** over the sample stage **12** via a support means **54**. In some embodiments, the plate electrode **50** has an opening **52** therethrough to allow access to the sample stage **12** from the normal. The plate electrode **50** is in electrical contact with an electrode **70**, which is in turn in electrical contact with wire trace **72**. The wire trace **72** is in electrical contact with a bond pad **74** that receives wire **76**.

In operation, a voltage is delivered to the plate electrode **50** via the wire **76**, bonding pad **74**, wire trace **72** and electrode **70**. An electrostatic force is generated between the sample stage **12** and the plate electrode **50** that causes the sample stage to move out-of-plane towards the plate electrode. Using a precision capacitance bridge, the position of the sample stage **12** can be sensed and controlled to within about 20 nm or less in the z-direction. Thus, the plate electrode **50** and associated elements, in conjunction with the x-drive means **20** and the y-drive means **40**, are collectively operable to move the sample stage **12** in three-dimensional space.

In preferred embodiments, support means **54** is an arrangement of hinged plates suitably-configured for lifting the plate electrode **50** and permanently suspending it over the sample stage **12**. The hinged plates utilized in conjunction with the present invention are well known to those skilled in micromachining technology. See, for example, Pister et al., "Microfabricated Hinges," vol. 33, Sensors and Actuators A, pp. 249-56, 1992, incorporated by reference herein. Technology for fabricating such hinges and micro devices formed therefrom is available from MEMS Technology Application Center at North Carolina (MCNC) under Defense Advanced Research Projects Agency (DARPA)-supported Multi-User MEMS Processes (MUMPs). MCNC MUMPs technology utilizes three polysilicon layers in which hinged plates are formed using photolithographic methods. See also assignee's co-pending patent applications MICRO MACHINED OPTICAL SWITCH filed May 15, 1997 as Ser. No. 08/856,569; METHOD AND APPARATUS FOR MAKING A MICRO DEVICE filed May 15, 1997 as Ser. No. 08/856,565, both of which applications are incorporated by reference herein.

An exemplary embodiment of support means **54** utilizing such hinged plates is illustrated in FIG. 5. For clarity of illustration, the xy stage **4** and associated elements are not shown in FIG. 5. In the embodiment illustrated in FIG. 5, the support means **54** comprises two hinged support plates **55**, and two hinged support plate locks **63**. As shown in FIGS. 5 and 6, each support plate **55** includes hinges **57**, a plurality of openings **56** and two risers **60**. The openings **56** receive conductive fingers **58** that depend from electrodes **70** at one end, and the plate electrode **50** at the other end. The fingers **58** are dual function. One function is for providing electrical connection to the plate electrode **50**. A second function is to aid in assembling the plate electrode **50**/support means **54**, as described below.

The various plates, electrodes and other elements comprising the present xyz stage are patterned in one of two

polysilicon layers deposited on the support surface **10**, such as by using the MCNC MUMPs process. Such elements are disposed in the plane of the support surface **10** when they are formed. It will be appreciated that to form the z-drive means shown in FIG. **5**, those elements must be either rotated (the support plates **55**, the support plate locks **63**) or lifted (the plate electrode **50**) out of the plane of the support surface **10**.

The plate electrode **50** may be lifted off the support surface **10** by lifting the unhinged end of each support plate **55** so that the support plate rotates about hinge **57**. FIG. **6** illustrates such lifting and rotation, along the path **82**, for one of the support plates **55**. As a support plate **55** is rotated in the illustrated direction, the fingers **58** passing through openings **56** in the support plates are moved upwardly relative to the support surface **10**. As the fingers **58** are attached to the plate electrode **50**, it is likewise moved out-of-plane.

The plate electrode **50** is lifted off the support surface **10** to a final position, typically about 30 microns over the support surface. When the plate electrode **50** is at that position, the support plates **55** assume a substantially vertical orientation relative to the support surface **10**. The support plates **55** may be fixed in the aforementioned vertical orientation via support plate locks **63**. In the exemplary embodiment shown in FIG. **5**, each support plate lock **63** comprises two hinged plates **62a**, **62b** and interconnecting member **64**. Each hinged plate **62a**, **62b** has a slot **66** formed at the unhinged end. To fix the support plates **55** in position, the support plate locks **63** are lifted, such as by placing a micropipette under the interconnecting member **64**. As each support plate lock is lifted, it rotates about hinge **68** towards the suspended plate electrode and support plates **55**. Rotation about the hinge **68** along a path **84** is illustrated for one of the support plate locks **63** in FIG. **7**. Such rotation continues until slot **66** engages a projection or riser **60** disposed at each end of support plates **55**. In addition, an adhesive can be placed on the hinges **57**, **68** and in slots **66** engaging risers **60** to prevent the support plate **55** or the support plate locks **63**, respectively, from moving. The adhesive can be applied according to a method described in the assignee's copending patent application entitled METHOD FOR FORMING MICRON-SIZED AND SMALLER LIQUID DROPLETS filed May 15, 1997 as Ser. No. 08/856,566, incorporated by reference herein.

It will be appreciated that a variety of other arrangements for lifting and supporting plate electrode **50** and for forming a parallel plate actuator and associate support means, can be utilized in conjunction with the present invention.

The present xyz stage may be advantageously used in conjunction with optical elements. For example, in one embodiment, the xyz stage is used in combination with an optical fiber having a micron- or smaller-sized aperture for forming a near-field scanning optical microscope (NSOM).

Near-field microscopes work by using a very small aperture to "focus" light to a small spot size. The spot size can be many times smaller than the wavelength λ of light. The light is scanned over a sample, and collected by far field optics. The collected light is then delivered to processing electronics for measuring intensity or other optical properties and for processing the measurements into an image. See Betzig et al., "Near-Field Optics: Microscopy, Spectroscopy, and Surface Modification Beyond the Diffraction Limit," vol. 257, Science, pp. 189-195, Jul. 10, 1992, incorporated by reference herein.

A NSOM according to the present invention is shown in FIG. **8**. For clarity of presentation, neither the x- nor y- drive

means **20**, **40**, are pictured, and the support means **54** is figuratively illustrated. It should be understood that the present NSOM comprises an xyz stage according to the present invention, as well as an optical fiber **90** having a reduced-sized aperture **92**. The opening **52** in the plate electrode **50** provides the optical fiber **90** access to the sample stage **12**.

As presently implemented, the aperture, which has a diameter typically in the range of about 50 to 100 nanometers (nm), can be formed by drawing down the tip of an optical fiber by known methods. According to one such method, tension is placed on the fiber, and the fiber is heated locally with a focused laser spot. As the fiber heats it begins to flow and separates into two pieces with finely tapered ends. Metal is then deposited at the tapered fiber ends, leaving a small opening at the tip.

It is important to maintain a substantially constant-sized gap between the fiber aperture **92** and the sample stage **12**. This is conventionally accomplished by measuring shear force. According to such conventional practice, the fiber, such as the fiber **90** of the present invention, is oscillated using a piezo. The sample stage, such as the sample stage **12**, is moved upwardly towards the fiber until some characteristic of the fiber's motion changes. For example, the amplitude of the motion may decrease. Such a change, e.g., a decrease in amplitude, occurs when, due to the proximity of the tip of the fiber to the sample surface, a shear force acts on the fiber tip. The characteristics, e.g., amplitude and frequency, of fiber oscillation can be monitored by observing the same piezo that is used to drive the fiber. In such a case, the AC impedance of the piezo is measured. Alternatively, an additional light source/detector can be used.

In a method according to the present invention, gap size is maintained by monitoring changes in mechanical loss while oscillating the sample stage **12** in the z-direction with an amplitude of about 50 nm. The present method advantageously avoids the shear forces utilize by prior art methods, which can degrade delicate samples. According to the present method, a capacitance bridge is connected to the plate electrode **50** and the sample stage **12**. The output from the bridge is capacitance, C, and loss, G. In simplified terms, the bridge applies voltage and measures current. The applied voltage equals the sum of the dc and ac voltage components; i.e., $V_{app} = V_{DC} + V_{AC}$. The dc voltage, which typically is in the range of 0 to about 40 volts, determines the position of the sample stage **12** in the z-direction, i.e., moving towards the plate electrode **50**. The ac voltage is typically a much lower value. Only the ac component of the current is measured. The phase sensitive measurement facilitates determining both the capacitive (C) and resistive (G) components of the impedance of the sample stage and plate electrode.

The position of the stage can be determined theoretically based on the physical dimensions of the sample stage (**12**) and plate electrode (**50**), etc. and the capacitance measurement. A capacitance/position relationship can then be developed. Preferably, actual measurements of the sample stage (**12**) and plate electrode (**50**) spacing are taken in conjunction with capacitance measurements for different applied voltages. In this manner, capacitance may be used to determine the position in the z-direction as a function of dc voltage.

The ac voltage, having a frequency lower than the resonance frequency of the xyz stage, is used to oscillate the stage mechanically around its equilibrium position, as determined by V_{DC} . If the probe tip is in the vicinity of the

surface of an empty sample stage **12**, or of the surface of a sample mounted thereon, forces acts between the tip and the surface. The force affects the oscillation amplitude of the stage. Oscillation amplitude is determined by V_{AC} , V_{DC} and mechanical losses, as well as by ac frequency. Since electric losses are negligible, all energy dissipation is due to mechanical loss. Mechanical loss, which is due to air damping, is proportional to the amplitude of the oscillation. Thus, changes in such amplitude can be seen by changes in G . The proximity of the tip to such surface can thus be determined.

Moreover, the present method can be used for tip-to-sample proximating determination by oscillating the sample stage **12** in the x or y directions, as well as in the z-direction. In such a case, the method is a modification of shear force feedback.

Although not pictured in the drawings, the present NSOM also includes controlled voltage sources for actuating the x-drive, y-drive and z-drive and for controlling movement imparted to the sample stage via the x-drive, y-drive and the z-drive. Additionally, as previously noted, the capacitance of the z-drives and/or x- and y-drives can be measured to control sample stage movement.

Additionally, the NSOM includes far-field optics operable to collect light reflected from, or transmitted through, a sample on the sample stage. Such optics typically includes an objective lens for collecting reflected/transmitted light, and optics to deliver such light to a detector, and the detector. The detector can be a photomultiplier, although a variety of other light detectors suitable for measuring intensity and other characteristics may suitably be used. For example, polarization, time delay, and changes in polarization, spectrum and the like may suitably be used. The detector is, in turn, connected to a processor suitably configured or programmed for processing the intensity/contrast measurements into an image.

In a first exemplary embodiment, the NSOM can be arranged on a table top. In such an embodiment, a conventional microscope can advantageously be used to provide the far-field optics. In particular, the objective lens, and other optics of a conventional microscope for delivering light to a camera port of the microscope are used, in conjunction with a commercial lightmeter mounted on that port.

In a second exemplary embodiment, the NSOM can be arranged within a cryostat for low temperature studies, such as for studying superconductivity. In such an embodiment, the far-field optics comprise a grin lens, a fiberoptic image conduit for delivering light out of the cryostat, and a lightmeter.

As though skilled in the art will appreciate, the far-field collection optics, and illumination optics (not discussed), typically include polarizers, filters, and a variety of other components, as well. See, for example, Betzig et al., "Near-Field Optics: Microscopy, Spectroscopy, and Surface Modification Beyond the Diffraction Limit," previously referenced.

In a further embodiment of the present invention, a scanning probe microscopy (SPM) probe, not shown, can be disposed on the present xyz stage. In some embodiments, such a probe can be fabricated by micromachining, such as, for example, a micromachined silicon tip. The SPM probe allows the present xyz stage to be used, for example, for atomic force microscopy (AFM) or scanning tunneling microscopy (STM).

Both AFM and STM involve the accurate movement and position detection of a sharp sensing tip. See Indermuehle et

al. in "Design and Fabrication of an Overhanging xy-Microactuator with Integrated Tip for Scanning Surface Profiling," vol. 43, Sensors and Actuators A, pp. 346-50 (1994), incorporated by reference herein.

Although specific embodiments of this invention have been described herein, it is to be understood that these embodiments are merely illustrative of the principles of this invention. Numerous and varied modifications may occur to, and be implemented by, those of ordinary skill in the art in view of the present teachings without departing from the scope and the spirit of the invention.

We claim:

1. An xyz stage operable for movement in three dimensions, comprising:

a sample stage;

a x-drive physically configured to move the sample stage along a first axis;

a y-drive physically configured to move the sample stage along a second axis, wherein the second axis is co-planar with the first axis; and

a z-drive physically configured to move the sample stage along a third axis that is orthogonal to the first and second axes, said z-drive comprising:

said sample stage and an electrode, said electrode being suspended over said sample stage by a support that includes a support plate that is rotatably-attached to a support surface.

2. The xyz stage of claim 1, wherein said electrode is a plate electrode.

3. The xyz stage of claim 2, wherein said support plate has openings that receive electrically-conductive members depending from the plate electrode.

4. The xyz stage of claim 3, wherein said conductive members are in electrical communication with voltage-receiving means.

5. The xyz stage of claim 2, further comprising a capacitance bridge that is electrically connected to said sample stage and said plate electrode.

6. The xyz stage of claim 1, wherein the support plate is rotatably-attached to the support surface by a hinge.

7. The xyz stage of claim 6, wherein the support further comprises a support plate lock for fixing the support plate in an orientation that is out of plane relative to the support surface.

8. The xyz stage of claim 7, wherein the support plate lock comprises a plate rotatably-attached to the support surface, and further wherein the plate is physically adapted to engage a projection depending from the support plate.

9. The xyz stage of claim 8, wherein the support plate lock is rotatably-attached to the support surface by a hinge.

10. The xyz stage of claim 1, wherein the x-drive is a comb drive.

11. The xyz stage of claim 10, wherein said y-drive is a comb-drive.

12. The xyz stage of claim 10, wherein said comb-drive comprises: interdigitated movable teeth members and fixed teeth members, wherein:

said movable teeth members are mechanically linked to said sample stage, and said fixed teeth members are mechanically linked to said support surface.

13. The xyz stage of claim 12, said comb-drive further comprising a drive stage, wherein:

said movable teeth members depend from a first portion of said drive stage;

a linkage depends from a second portion of said drive stage, said linkage mechanically linking said drive stage to said sample stage.

9

14. The xyz stage of claim **13**, said comb-drive further comprising a drive support that depends from said drive stage and supports said drive stage above said support surface.

15. The xyz stage of claim **14**, wherein said drive support is electrically conductive and is operable to deliver a voltage to said drive stage.

10

16. The xyz stage of claim **14**, wherein said drive support has a folded beam configuration.

17. The xyz stage of claim **14**, wherein said drive support, said drive stage and said sample stage comprise polysilicon.

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