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(54) **SCANNING PROBE MICROSCOPE**

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(57) **ABSTRACT**

A scanning probe microscope is configured to measure a topography of a sample. The microscope includes a probe mount and a cantilever carried by the probe mount. The cantilever extends from a proximal end at the probe mount to a distal end remote from the probe mount. The microscope also includes a probe tip at the distal end of the cantilever, a scanning system configured to generate a relative scanning motion between the probe mount and the sample, and an interferometer configured to measure a height of the distal end of the cantilever to generate a height measurement signal. The microscope further includes a signal processor configured to monitor the height measurement signal to obtain a series of topography measurements indicative of a topography of the sample, a height actuation system configured to adjust a height of the proximal end of the cantilever by moving the probe mount under control of a height control signal, a photothermal actuation system configured to bend the cantilever by illuminating the cantilever with an actuation beam under control of a photothermal offset signal and an oscillation signal, an oscillation signal generator configured to generate the oscillation signal, and a control system configured to adjust the photothermal offset signal and the height control signal on a basis of the height measurement signal.

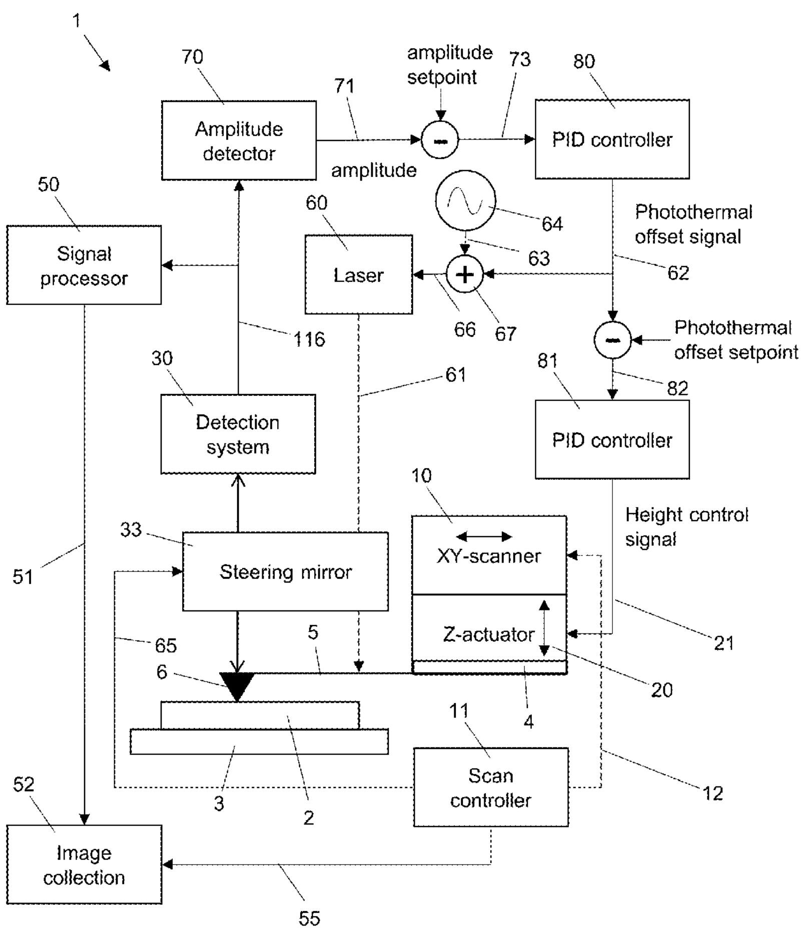
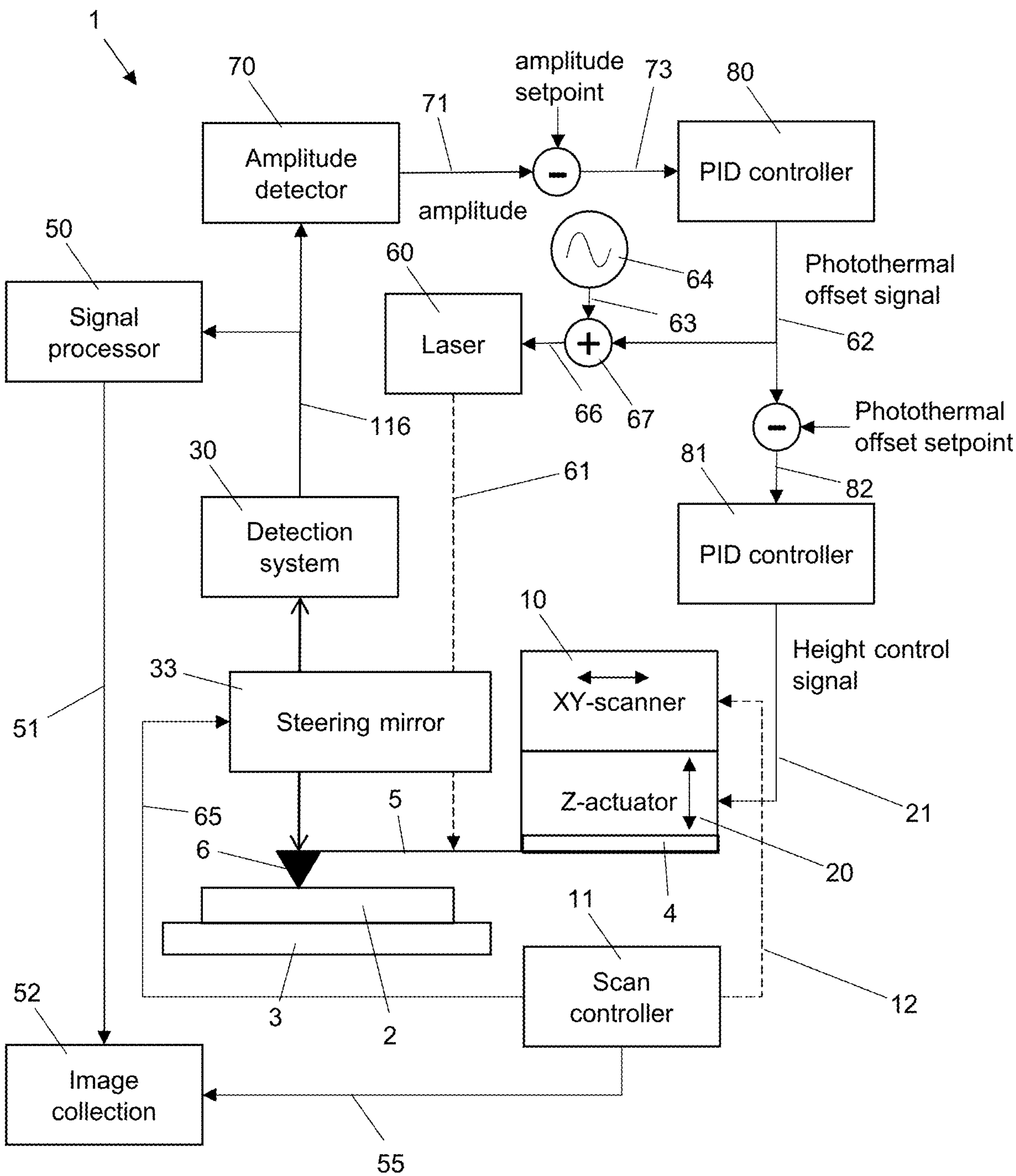


FIG. 1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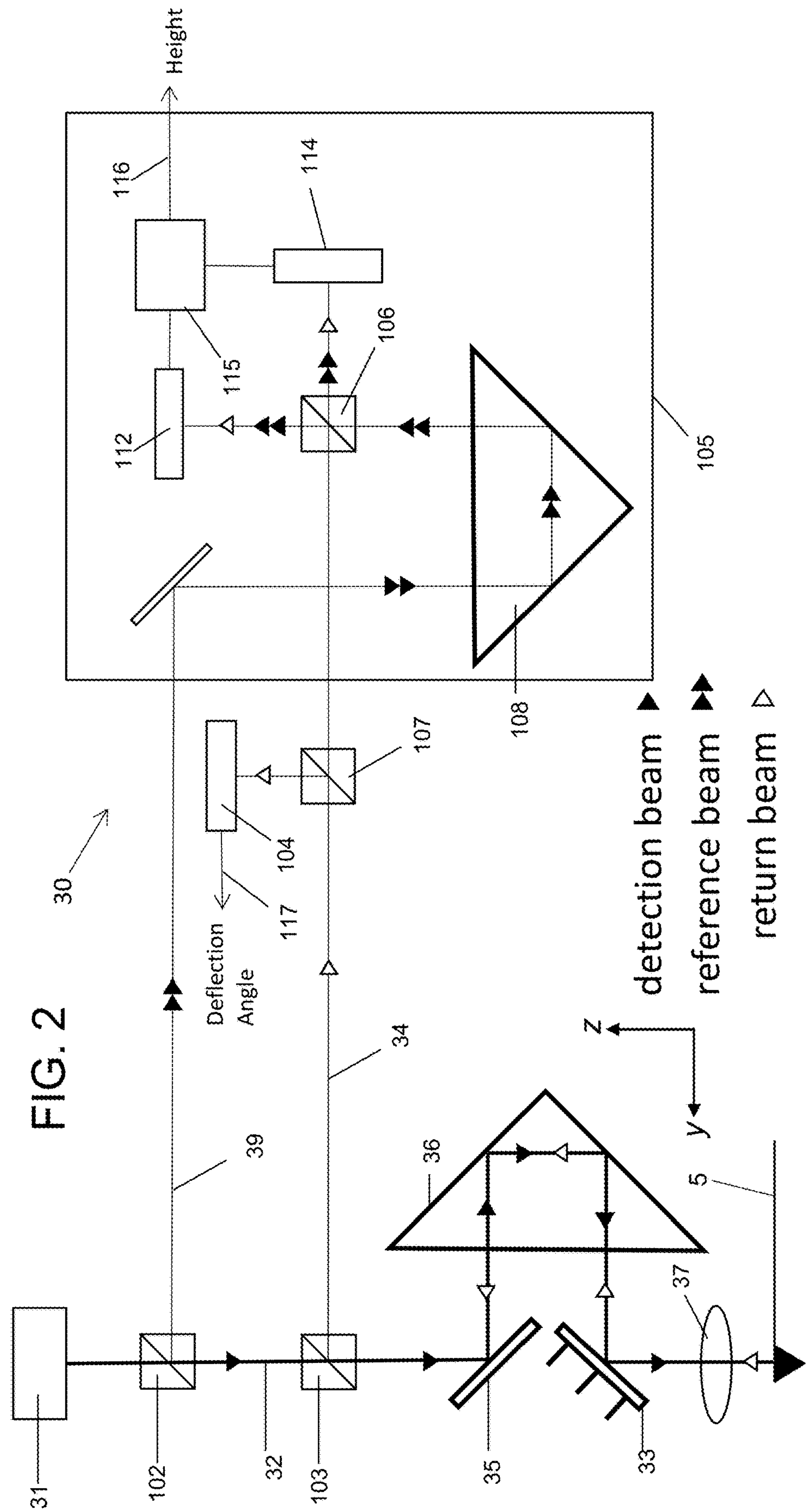
71
amplitude
amplitude setpoint
73
80
PID controller
50
Signal processor
60
Laser
64
63
Photothermal offset signal
62
66
67
116
Photothermal offset setpoint
30
Detection system
61
81
82
PID controller
10
XY-scanner
Height control signal
33
Steering mirror
51
Z-actuator
21
65
5
6
20
4
11
Scan controller
12
3
2
52
Image collection
55

FIG. 2


Height
116
114
115
112
106
105
108
107
104
Deflection Angle
117
30
39
34
36
z
y
5
37
31
102
32
103
35
33
detection beam
reference beam
return beam

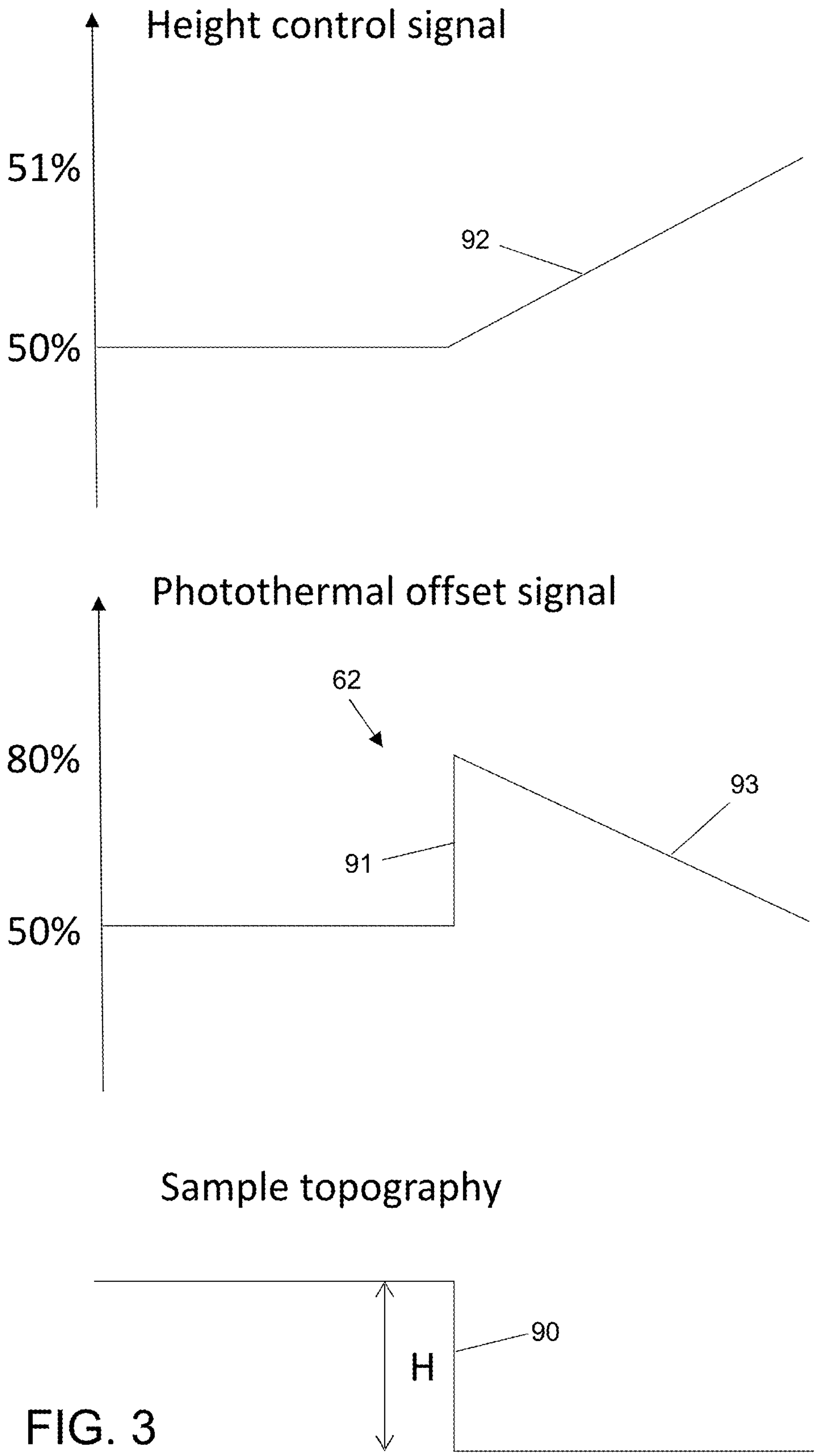

Height control signal
51%
92
50%
Phototermal offset signal
62
80%
93
91
50%
Sample topography
90
H

FIG. 3

FIG. 4

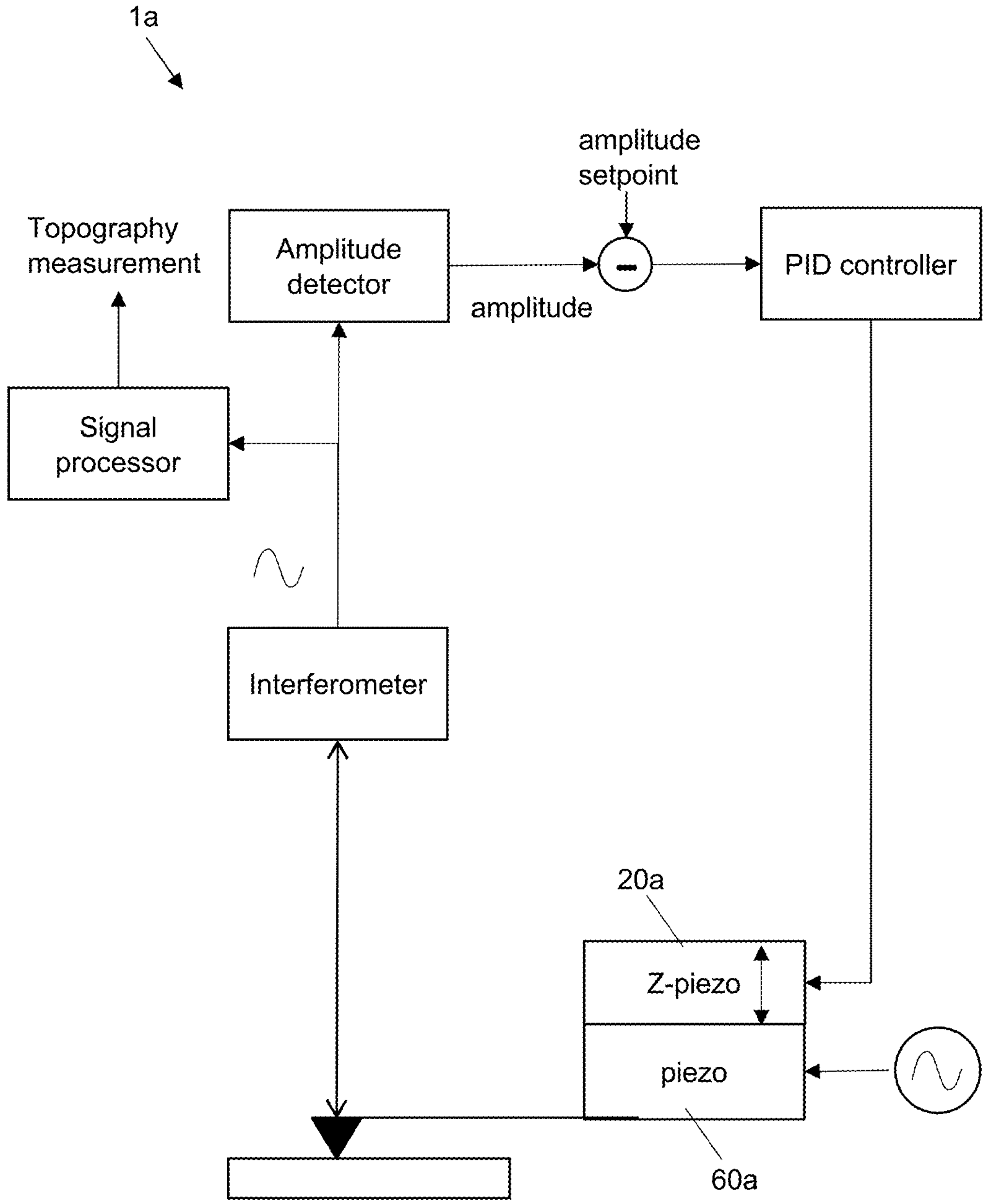

1a
amplitude
setpoint
Topography
measurement
Amplitude
detector
PID controller
amplitude
Signal
processor
Interferometer
20a
Z-piezo
piezo
60a

FIG. 5

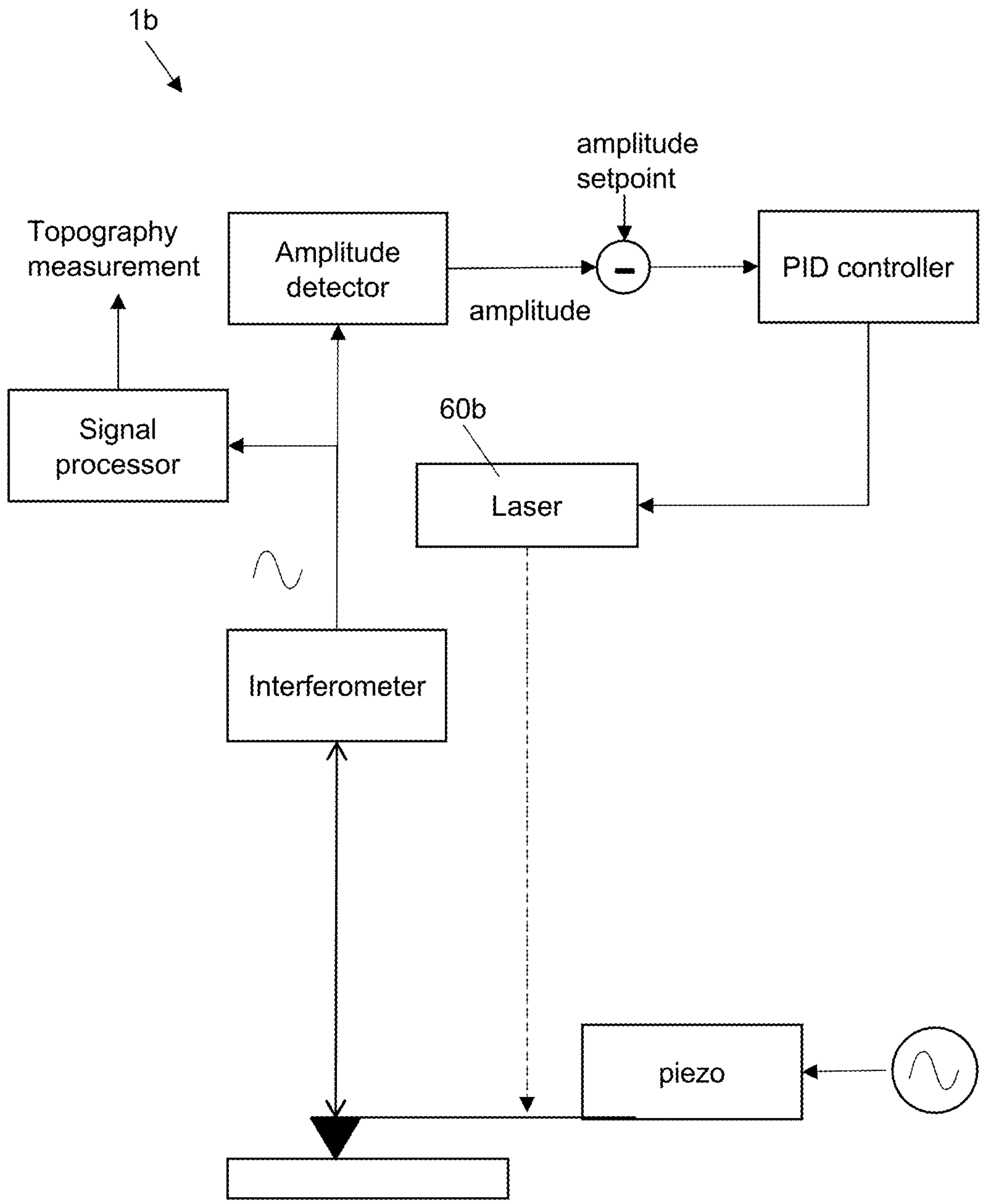
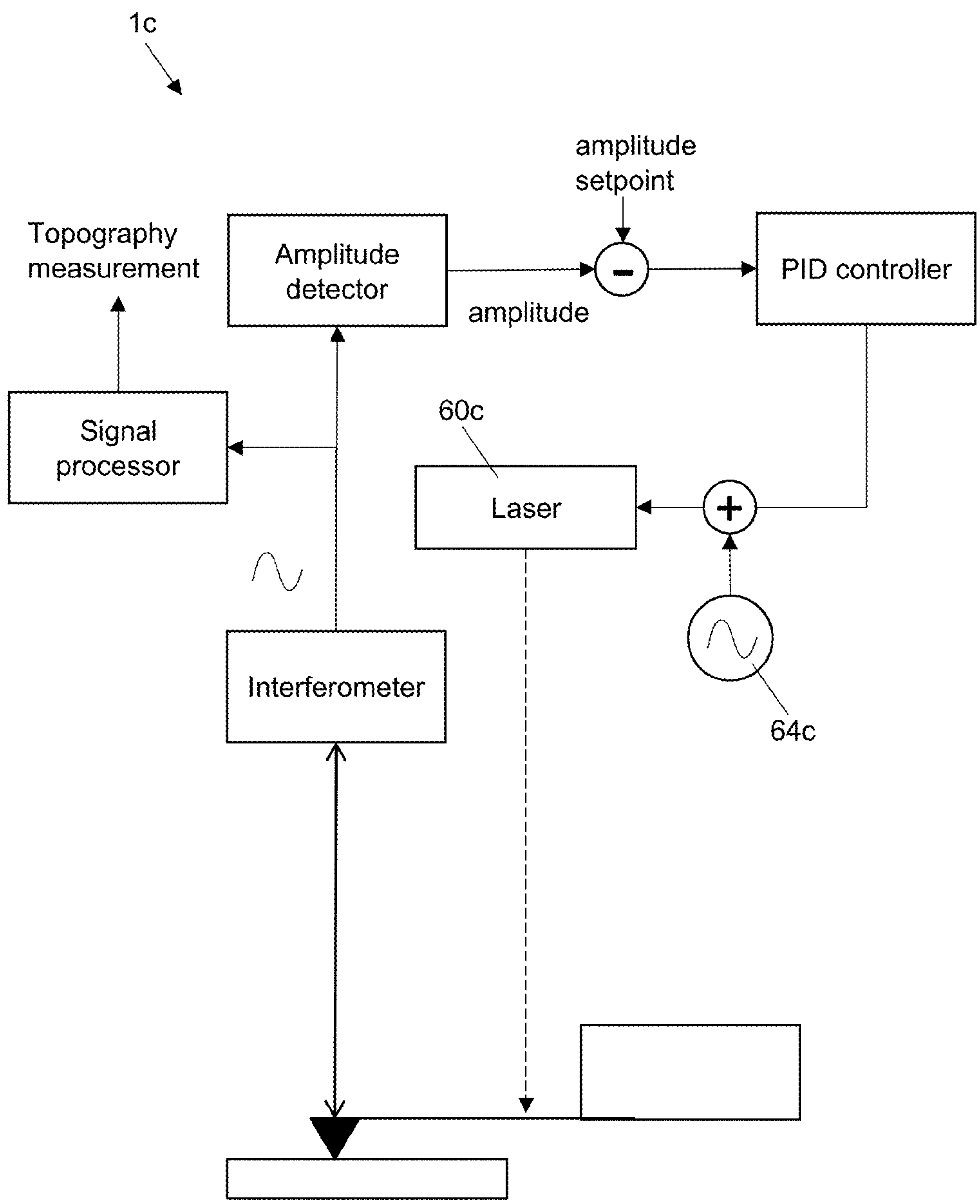

1b
amplitude
setpoint
Topography
measurement
Amplitude
detector
amplitude
PID controller
Signal
processor
60b
Laser
Interferometer
piezo

FIG. 6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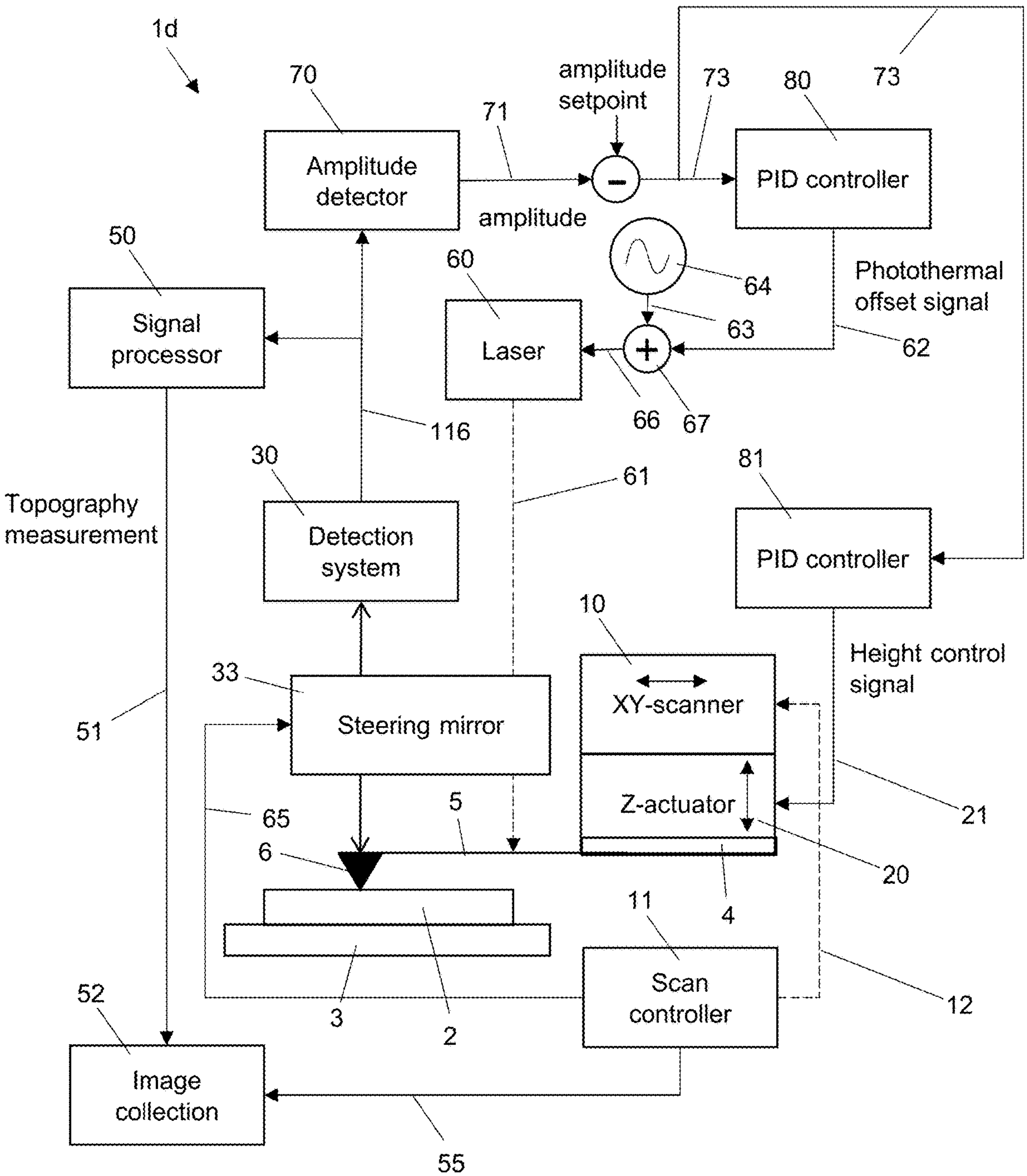
setpoint
Topography
measurement
Amplitude
detector
PID controller
amplitude
Signal
processor
60c
Laser
Interferometer
64c

FIG. 7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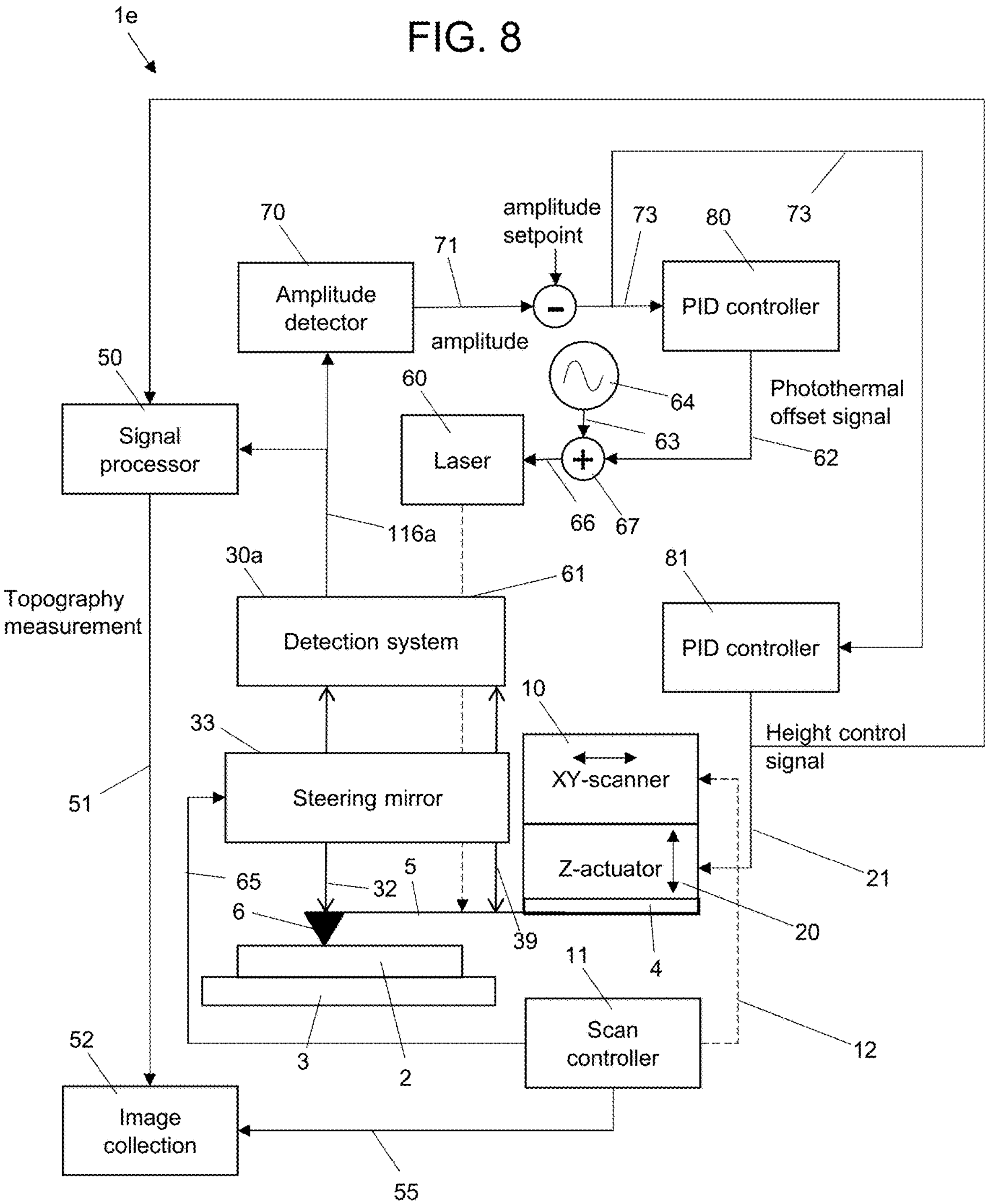
amplitude
amplitude setpoint
73
80
PID controller
73
Photothermal offset signal
64
63
62
60
Laser
66
67
50
Signal processor
116
30
Detection system
61
81
PID controller
Topography measurement
10
XY-scanner
Height control signal
33
Steering mirror
51
Z-actuator
21
65
5
6
20
4
11
Scan controller
12
3
2
52
Image collection
55

FIG. 8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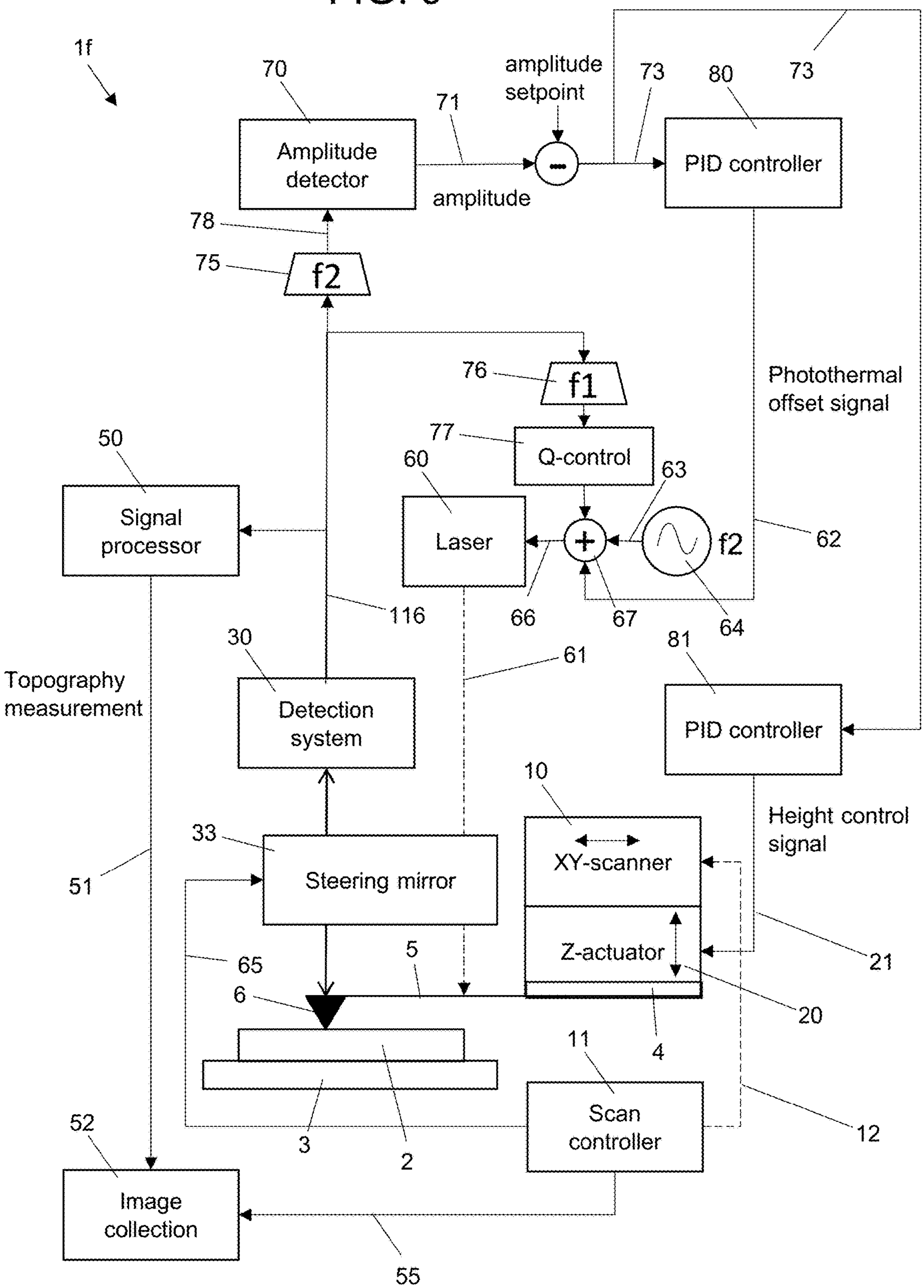
71
amplitude setpoint
amplitude
73
80
73
PID controller
50
Signal processor
60
Laser
64
63
Photothermal offset signal
62
66
67
116a
30a
61
81
Topography measurement
Detection system
PID controller
10
33
Steering mirror
XY-scanner
Height control signal
51
Z-actuator
21
65
32
5
6
39
20
11
4
Scan controller
12
3
2
52
Image collection
55

FIG. 9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71
amplitude
amplitude setpoint
73
80
73
PID controller
78
75
f2
76
f1
77
Q-control
Photothermal offset signal
50
Signal processor
60
Laser
63
f2
62
66
67
64
116
30
Detection system
61
81
PID controller
Topography measurement
10
XY-scanner
Height control signal
33
Steering mirror
51
Z-actuator
21
65
5
6
20
4
11
Scan controller
3
2
12
52
Image collection
55

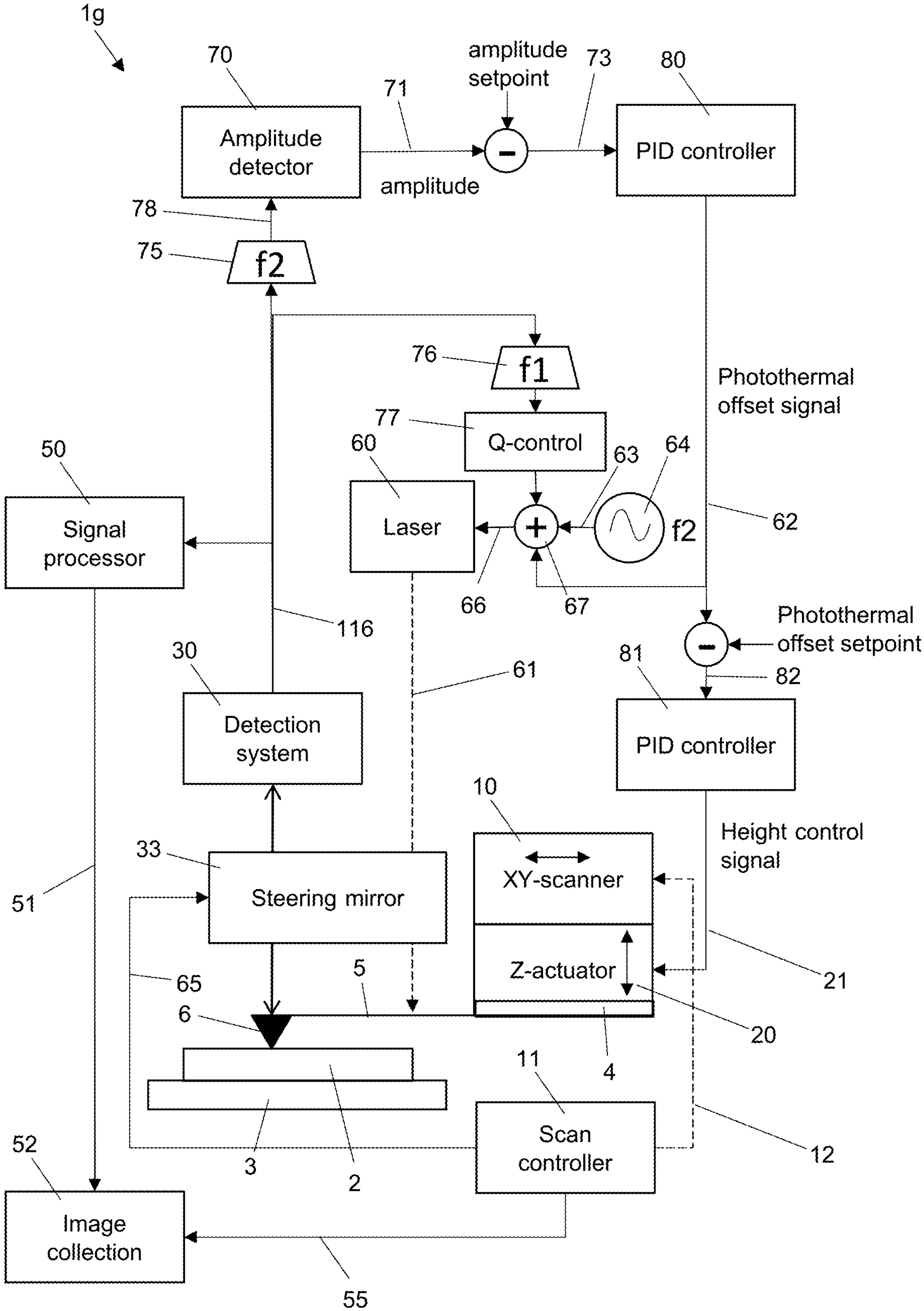
1g
70
Amplitude detector
71
amplitude setpoint
73
80
PID controller
amplitude
78
75
f2
76
f1
77
Q-control
60
Laser
63
64
f2
62
Photothermal offset signal
50
Signal processor
66
67
116
Photothermal offset setpoint
81
82
PID controller
30
Detection system
61
10
XY-scanner
Height control signal
33
Steering mirror
51
Z-actuator
21
65
5
6
20
11
4
3
2
Scan controller
12
52
Image collection
55

FIG. 10

SCANNING PROBE MICROSCOPE

TECHNICAL FIELD

[0001] The present invention relates to a scanning probe microscope, and an associated method.

BACKGROUND

[0002] WO2010067129A1 discloses a dynamic probe detection system for use with a scanning probe microscope of the type that includes a probe that is moved repeatedly towards and away from a sample surface. As a sample surface is scanned, an interferometer generates an output height signal indicative of a path difference between light reflected from the probe and a height reference beam. Signal processing apparatus monitors the height signal and derives a measurement for each oscillation cycle that is indicative of the height of the probe. This enables extraction of a measurement that represents the height of the sample, without recourse to averaging or filtering, that may be used to form an image of the sample. The detection system may also include a feedback mechanism that is operable to maintain the average value of a feedback parameter at a set level.

[0003] U.S. Pat. No. 6,189,374 discloses an AFM that combines an AFM Z position actuator and a self-actuated Z position cantilever (both operable in cyclical mode and contact mode), with appropriate nested feedback control circuitry to achieve high-speed imaging and accurate Z position measurements. A preferred embodiment of an AFM for analyzing a surface of a sample includes a self-actuated cantilever having a Z-positioning element integrated therewith and an oscillator that oscillates the self-actuated cantilever at a frequency generally equal to a resonant frequency of the self-actuated cantilever and at an oscillation amplitude generally equal to a setpoint value. The AFM includes a first feedback circuit nested within a second feedback circuit, wherein the first feedback circuit generates a cantilever control signal in response to vertical displacement of the self-actuated cantilever during a scanning operation, and the second feedback circuit is responsive to the cantilever control signal to generate a position control signal. A Z position actuator is also included within the second feedback circuit and is responsive to the position control signal to position the sample. In operation, preferably, the cantilever control signal alone is indicative of the topography of the sample surface.

[0004] Non-patent literature (NPL) [1] combines the fast response of photothermal cantilever excitation with a conventional piezoactuator, resulting in a fast force-clamp with high accuracy and large working distances.

[0005] NPL [2] applies photothermal bending of a cantilever induced by an intensity-modulated infrared laser to control the tip-surface distance in atomic force microscopy. The slow response of the photothermal expansion effect is eliminated by inverse transfer function compensation. By regulating the laser power and regulating the cantilever deflection, the tip-sample distance is controlled; this enables much faster imaging than that in conventional piezoactuator-based z scanners because of the considerably higher resonant frequency of small cantilevers.

[0006] In NPL [3] a flexible system for increasing the throughput of an atomic force microscope without sacrificing imaging range is presented. The system is based on a nested feedback loop which controls a micromachined cantilever that contains both an integrated piezoelectric actuator and an integrated thermal actuator.

[0007] NPL [1]: Stahl S W, Puchner E M, Gaub H E. Photothermal cantilever actuation for fast single-molecule force spectroscopy. Rev Sci Instrum. 2009 July; 80(7): 073702. doi: 10.1063/1.3157466. PMID: 19655951.

[0008] NPL [2]: Yamashita H, Kodera N, Miyagi A, Uchihashi T, Yamamoto D, Ando T. Tip-sample distance control using photothermal actuation of a small cantilever for high-speed atomic force microscopy. Rev Sci Instrum. 2007 August; 78(8):083702. doi: 10.1063/1.2766825. PMID: 17764324.

[0009] NPL [3]: T. Sulchek, S. C. Minne, J. D. Adams, D. A. Fletcher, A. Atalar, C. F. Quate, D. M. Adderton; Dual integrated actuators for extended range high speed atomic force microscopy. Appl. Phys. Lett. 13 Sep. 1999; 75 (11): 1637-1639. https://doi.org/10.1063/1.124779.

[0010] NPL [4]: Balantekin M, Satir S, Torello D, Değertekin F L. High-speed tapping-mode atomic force microscopy using a Q-controlled regular cantilever acting as the actuator: proof-of-principle experiments. Rev Sci Instrum. 2014 December; 85(12):123705. doi: 10.1063/1.4903469. PMID: 25554299.

[0011] NPL [5]: J. Mertz, O. Marti, J. Mlynek; Regulation of a microcantilever response by force feedback. *Appl. Phys. Lett.* 10 May 1993; 62 (19): 2344-2346. https://doi.org/10.1063/1.109413.

[0012] NPL [6]: M. G. Ruppert, B. S. Routley, A. J. Fleming, Y. K. Yong and G. E. Fantner, "Model-based Q Factor Control for Photothermally Excited Microcantilevers," 2019 *International Conference on Manipulation, Automation and Robotics at Small Scales* (*MARSS*), Helsinki, Finland, 2019, pp. 1-6, doi: 10.1109/MARSS.2019.8860969.

SUMMARY OF THE DISCLOSURE

[0013] A first aspect of the invention provides a scanning probe microscope configured to measure a topography of a sample, the scanning probe microscope comprising: a probe mount; a cantilever carried by the probe mount, the cantilever extending from a proximal end at the probe mount to a distal end remote from the probe mount; a probe tip at the distal end of the cantilever; a scanning system configured to generate a relative scanning motion between the probe mount and the sample; a detection system configured to measure the distal end of the cantilever to generate a measurement signal; a signal processor configured to monitor the measurement signal to obtain a series of topography measurements indicative of a topography of the sample; a height actuation system configured to adjust a height of the proximal end of the cantilever by moving the probe mount under control of a height control signal; a photothermal actuation system configured to bend the cantilever by illuminating the cantilever with an actuation beam under control of a photothermal offset signal and an oscillation signal; an oscillation signal generator configured to generate the oscillation signal; and a control system configured to adjust the photothermal offset signal and the height control signal on a basis of the measurement signal.

[0014] Optionally the control system is a feedback control system. Alternatively the control system is a feedforward control system. Alternatively the control system may use a combination of feedforward and feedback control, or another control method. Optionally the control system comprises an oscillation error detector configured to monitor the measurement signal to obtain an oscillation parameter and generate an oscillation error signal based on the oscillation parameter and an oscillation parameter setpoint; and the control system is configured to adjust the photothermal offset signal and the height control signal on a basis of the oscillation error signal.

[0015] Optionally the control system comprises: a first controller (for example a feedback controller or a feedforward controller) configured to adjust the photothermal offset signal; and a second controller (for example a feedback controller or a feedforward controller) configured to adjust the height control signal.

[0016] Optionally the second controller operates at a slower rate than the first controller, or operates with a longer response time than the first controller, or operates with a lower bandwidth than the first controller.

[0017] Optionally the first and second controllers operate over non-overlapping frequency bands.

[0018] Optionally the control system comprises: a first feedback controller configured to adjust the photothermal offset signal in order to null an input to the first feedback controller; and a second feedback controller configured to adjust the height control signal in order to null an input to the second feedback controller.

[0019] Optionally the input to the first feedback controller comprises the oscillation error signal.

[0020] Optionally the control system further comprises a photothermal error detector configured to generate a photothermal error signal based on the photothermal offset signal and a photothermal offset setpoint; and the input to the second feedback controller comprises the photothermal error signal.

[0021] Optionally the photothermal offset setpoint is at a mid-point of an operating range of the photothermal offset signal.

[0022] Optionally the input to the second feedback controller comprises the oscillation error signal.

[0023] Optionally the oscillation error signal is fed in parallel to the first and second feedback controllers.

[0024] Optionally the photothermal offset signal and the oscillation signal are distinct signals, wherein an intensity of the actuation beam is based on an addition (or other combination) of the photothermal offset signal and the oscillation signal. The photothermal offset signal and oscillation signal may be output by different components: for example, the photothermal offset signal may be output by the first feedback controller and the oscillation signal may be output by the oscillation signal generator.

[0025] Optionally the control system is configured to adjust the photothermal offset signal to respond to changes in the topography of the sample.

[0026] Optionally the scanning probe microscope further comprises a combiner configured to combine the oscillation signal and the photothermal offset signal to generate a combined signal, wherein the photothermal actuation system is configured to illuminate the cantilever with the actuation beam under control of the combined signal.

[0027] Optionally the combiner is an adder which combines the oscillation signal and the photothermal offset signal by adding the oscillation signal and the photothermal offset signal.

[0028] Optionally the oscillation signal causes the cantilever to bend in a series of oscillation cycles, and the signal processor is configured to obtain a topography measurement indicative of the topography of the sample for each oscillation cycle.

[0029] Optionally the signal processor is configured to extract data from a position within each oscillation cycle that satisfies a predetermined measurement criterion.

[0030] Optionally the position within each oscillation cycle is an extremal position.

[0031] Optionally the signal processor is configured to monitor the height signal and to derive a measurement for each oscillation cycle that is indicative of the height of the probe.

[0032] Optionally the photothermal actuation system has a higher bandwidth than the height actuation system.

[0033] Optionally the height actuation system has a larger range of motion (i.e. its full operating range) than the photothermal actuation system. Optionally the height actuation system has a range of motion (i.e. its full operating range) which is more than ten times higher than the photothermal actuation system. For instance the height actuation system may have a full operating range above 5 micron or above 10 micron.

[0034] Optionally the oscillation signal is substantially sinusoidal, although the oscillation signal may have a non-sinusoidal waveform such as a triangle waveform or a sawtooth waveform.

[0035] The oscillation signal may be at a resonant frequency of the cantilever, or at any other frequency.

[0036] The oscillation signal typically varies back and forth in a series of oscillation cycles. The oscillation signal may be periodic so that each oscillation cycle is the same, or it may be aperiodic so that the oscillation cycles vary from cycle to cycle.

[0037] Optionally the height actuation system comprises a piezoelectric actuator.

[0038] A further aspect of the invention provides a method of measuring a topography of a sample with a scanning probe microscope according to the first aspect, the method comprising: generating a relative scanning motion between the probe mount and the sample with the scanning system; measuring the distal end of the cantilever with the interferometer to generate a measurement signal; monitoring the measurement signal with the signal processor to obtain a series of topography measurements indicative of the topography of the sample; adjusting a height of the proximal end of the cantilever with the height actuation system by moving the probe mount under control of a height control signal; generating an oscillation signal with the oscillation signal generator; bending the cantilever with the photothermal actuation system by illuminating the cantilever with an actuation beam under control of a photothermal offset signal and the oscillation signal; and adjusting the photothermal offset signal and the height control signal with the control system on a basis of the measurement signal.

[0039] Optionally the photothermal offset signal is adjusted to respond to changes in the topography of the sample.

[0040] Optionally the cantilever is illuminated by separately generating the oscillation signal and the photothermal offset signal; combining the oscillation signal and the photothermal offset signal to generate a combined signal; and illuminating the cantilever with the actuation beam under control of the combined signal.

[0041] Optionally combining the oscillation signal and the photothermal offset signal comprises adding the oscillation signal and the photothermal offset signal.

[0042] Optionally the photothermal offset signal varies at a lower rate than the oscillation signal.

[0043] Optionally the cantilever has a fundamental eigenmode with a fundamental eigenmode frequency, and one or more higher-order eigenmodes each having a frequency higher than the fundamental eigenmode frequency, and the oscillation signal excites one of the higher-order eigenmodes.

[0044] Optionally the scanning probe microscope further comprises a Q-control module configured to apply a Q-control signal to the actuation beam to damp oscillation of the cantilever at the fundamental eigenmode frequency.

[0045] Optionally the scanning probe microscope further comprises a filter which is configured to filter the measurement signal by passing the frequency of the higher-order eigenmode and blocking the fundamental eigenmode frequency, thereby producing a filtered measurement signal, wherein the photothermal offset signal and the height control signal are adjusted by the control system on a basis of the filtered measurement signal.

[0046] Optionally the detection system is an interferometer and the measurement signal is a height measurement signal.

[0047] Optionally the detection system is an optical-lever and the measurement signal is a deflection measurement signal.

[0048] A further aspect of the invention provides a scanning probe microscope configured to measure a topography of a sample, the scanning probe microscope comprising: a probe mount; a cantilever carried by the probe mount, the cantilever extending from a proximal end at the probe mount to a distal end remote from the probe mount; a probe tip at the distal end of the cantilever; a scanning system configured to generate a relative scanning motion between the probe mount and the sample; a detection system configured to measure the distal end of the cantilever to generate a measurement signal; a signal processor configured to monitor the measurement signal to obtain a series of topography measurements indicative of a topography of the sample; a height actuation system configured to adjust a height of the proximal end of the cantilever by moving the probe mount under control of a height control signal; an actuation system configured to bend the cantilever under control of an oscillation signal; an oscillation signal generator configured to generate the oscillation signal; and a control system configured to adjust the height control signal on a basis of the measurement signal, wherein the cantilever has a fundamental eigenmode with a fundamental eigenmode frequency, and one or more higher-order eigenmodes each having a frequency higher than the fundamental eigenmode frequency, and the oscillation signal excites one of the higher-order eigenmodes.

[0049] Optionally the actuation system is a photothermal actuation system configured to bend the cantilever by illuminating the cantilever with an actuation beam under control of the oscillation signal. Alternatively the actuation system may use a piezoelectric actuation element or some other means of bending the cantilever.

[0050] Optionally the detection system is an interferometer and the measurement signal is a height measurement signal. Alternatively the detection system is an optical-lever and the measurement signal is a deflection measurement signal.

[0051] Optionally the scanning probe microscope further comprises a filter which is configured to filter the measurement signal by passing the frequency of the higher-order eigenmode and blocking the fundamental eigenmode frequency, thereby producing a filtered measurement signal, wherein the height control signal is adjusted by the control system on a basis of the filtered measurement signal.

[0052] The height actuation system typically uses a different actuator (which is typically also a different actuator-type) than the actuation system which is configured to bend the cantilever. For instance the height actuation system may use a piezoelectric actuator and the actuation system may use a photothermal actuator.

[0053] Optionally the height actuation system has a larger range of motion (i.e. its full operating range) than the actuation system which is configured to bend the cantilever. Optionally the height actuation system has a range of motion (i.e. its full operating range) which is more than ten times higher than the actuation system which is configured to bend the cantilever. For instance the height actuation system may have a full operating range above 5 micron or above 10 micron.

BRIEF DESCRIPTION OF THE DRAWINGS

[0054] Embodiments of the invention will now be described with reference to the accompanying drawings, in which:

[0055] FIG. **1** shows a scanning probe microscope according to a first embodiment of the present invention;

[0056] FIG. **2** shows a detection system;

[0057] FIG. **3** shows a sample topography, with an associated photothermal offset signal and height control signal;

[0058] FIG. **4** shows a first comparative example;

[0059] FIG. **5** shows a second comparative example;

[0060] FIG. **6** shows a third comparative example;

[0061] FIG. **7** shows a scanning probe microscope according to a second embodiment of the present invention;

[0062] FIG. **8** shows a scanning probe microscope **1***e* according to a further alternative embodiment of the invention;

[0063] FIG. **9** shows a scanning probe microscope **1***e* according to a further alternative embodiment of the invention; and

[0064] FIG. **10** shows a scanning probe microscope **1***e* according to a further alternative embodiment of the invention.

DETAILED DESCRIPTION

[0065] A scanning probe microscope **1** shown in FIG. **1** is configured to measure a topography of a sample **2** on a sample stage **3**.

[0066] The various functional elements of the microscope shown in FIG. **1** may be implemented in computer software running on one or more computer processors, or in dedicated hardware.

[0067] The scanning probe microscope **1** comprises a probe mount **4**; and a probe comprising a cantilever **5** and probe tip **6**. The cantilever **5** is carried by the probe mount **4**, the cantilever **5** extending from a proximal end at the probe mount to a distal end remote from the probe mount. The probe tip **6** is at the distal end of the cantilever **5**.

[0068] A scanning system **10**, **11** is configured to generate a relative scanning motion between the probe mount **4** and the sample **2** in a horizontal (X,Y) plane. In this case the relative scanning motion is achieved by motion of the probe mount **4**, but in other embodiments the relative scanning motion may achieved by motion of the sample stage **3**.

[0069] A height actuation system **20** is configured to adjust a height of the proximal end of the cantilever by moving the probe mount **4** under control of a height control signal **21**.

[0070] The height actuation system in this case comprises a Z-actuator **20**, such a piezoelectric actuator, which is configured to translate the probe mount **4** up and down in an essentially vertical (Z) direction on a basis of the height control signal **21**.

[0071] The scanning system in this case comprises an XY-scanner **10**, such as a pair of piezoelectric actuators which each move the Z-actuator **20** and the probe mount **4** in a respective horizontal direction (X or Y). The XY-scanner **10** is driven by scanning drive signals **12** from a scan controller **11**.

[0072] A detection system **30** is shown schematically in FIG. **1** and in further detail in FIG. **2**.

[0073] A laser light source **31** generates a detection beam **32** which is steered onto the distal end of the cantilever **5** by a steering mirror **33**. The distal end of the cantilever **5** reflects the detection beam **32** to generate a return beam **34**.

[0074] The detection beam **32** is reflected from a fixed mirror **35** towards a right-angle block **36**. The right angle block **36** is oriented such that the detection beam **32** is incident normally on the entry face. The detection beam **32** propagates to the steering mirror **33** and is reflected towards an objective lens **37**. As the steering mirror **33** tilts, the reflected detection beam **32** deflects, with the result that the angle and point of incidence of the detection beam **32** into the objective lens **37** changes. Synchronisation of the angle of the steering mirror **33** with the XY scanning pattern followed by the probe mount **4** as it is driven by the XY scanner **10** means that the detection beam **32** retains its position on the distal end of the cantilever **5**.

[0075] The light from the laser light source **31** is split by a beam splitter **102** into the detection beam **32** and a reference beam **39**. The return beam **34** is directed into the detection system **30** by a second beam splitter **103**. The return beam **34** is then split by a third beam splitter **107** into a first component which falls on a split photodiode **104**, and a second component which is directed into an interferometer **105**.

[0076] The split photodiode **104** is a position sensitive detector which generates a deflection measurement signal **117** in accordance with an offset of the first component of the return beam **34** relative to the split photodiode **104**. The deflection measurement signal **117** is indicative of a deflection angle of the cantilever. Typically the split photodiode **104** is split into four quadrants, the ratios between the signals from the four quadrants indicating offsets in X and Y of the first component of the return beam **34** relative to the split photodiode **104**.

[0077] Inside the interferometer **105**, the second component of the return beam **34** is split by a beam splitter **106**. The reference beam **39** is directed onto a retroreflector **108** and thereafter to the beam splitter **106**. The beam splitter **106** has an energy absorbing coating and splits both the return beam **34** and the reference beam **39** to produce first and second interferograms with a relative phase shift of ~90°. The two interferograms are detected respectively at photodetectors **112**, **114**.

[0078] Ideally, the photodetector signals are complementary sine and cosine signals with a phase difference of 90°. Further, they should have no dc offset, have equal amplitudes and only depend on the position of the cantilever and wavelength λ of the laser. Known methods are used to monitor the outputs of the photodetectors **112**, **114** while changing the optical path difference in order to determine and to apply corrections for errors arising as a result of the two photodetector signals not being perfectly harmonic, with equal amplitude and in phase quadrature. Similarly, dc offset levels are also corrected in accordance with methods known in the art.

[0079] These photodetector signals are suitable for use with a conventional interferometer reversible fringe counting apparatus and fringe subdividing apparatus, which may be provided as dedicated hardware or as a programmed computer. Phase quadrature fringe counting apparatus is capable of measuring displacements in the position of the cantilever to an accuracy of $\lambda/8$. That is, to 66 nm for light with a wavelength of 532. Known fringe subdividing techniques, based on the arc tangent of the signals, permits an improvement in accuracy to the nanometre scale or less. Interferometric methods of extracting the path difference between two coherent beams are well known in the art and so will not be described in any further detail. In FIG. **2** a processor **115** is shown which receives the signals from the photodetectors **112**, **114** and performs the fringe counting and subdividing mentioned above to generate a height measurement signal **116**.

[0080] In summary, the interferometer **105** is arranged to detect a path difference between light **34** reflected from the distal end of the cantilever and a height reference beam **39**. The height measurement signal **116** is indicative of this path difference, and hence indicative of a height of the distal end of the cantilever **5**.

[0081] Returning to FIG. **1**: a signal processor **50** is configured to monitor the height measurement signal **116** to obtain a series of topography measurements indicative of a topography of the sample. These topography measurements may be output as a topography measurement signal **51** to an image collection module **52**.

[0082] A photothermal actuation system **60**, such as a laser, is configured to bend the cantilever **5** by illuminating the cantilever with an actuation beam **61** under control of a photothermal offset signal **62** and an oscillation signal **63**. An oscillation signal generator **64** is configured to generate the oscillation signal **63**. The oscillation signal **63** may be substantially sinusoidal, at a resonant frequency of the cantilever **5**. Typically the resonant frequency of the cantilever is a few hundred kHz but it can be over 1 MHz.

[0083] The cantilever **5** has a fundamental eigenmode with a fundamental eigenmode frequency (denoted f1) and one or more higher-order eigenmodes each having a frequency (denoted f2, f3 etc) higher than the fundamental eigenmode frequency f1. Typically the oscillation signal **63** in the scanning probe microscope **1** of FIG. **1** excites the fundamental eigenmode, but in other embodiments the oscillation signal **63** may excite one of the higher-order eigenmodes.

[0084] The oscillation signal **63** may be a periodic signal which repeats at regular intervals, typically at a frequency higher than 1 MHz. The photothermal offset signal **62** may be an aperiodic signal, separate from the oscillation signal **63**, which is adjusted to respond to changes in the topography of the sample. Typically the photothermal offset signal **62** varies at a lower rate than the oscillation signal **63**, i.e. at a frequency lower than the resonant frequency of the cantilever **5**.

[0085] In this example the oscillation signal **63** is substantially sinusoidal, but in other embodiments the oscillation signal **63** may have a non-sinusoidal waveform such as a triangle waveform or a sawtooth waveform.

[0086] The oscillation signal **63** varies back and forth in a series of oscillation cycles. Each oscillation cycle may be the same, or the oscillation cycles may vary from cycle to cycle (for instance with different periods from cycle to cycle).

[0087] In general terms the oscillation signal **63** is typically an AC signal (which typically varies continuously) whereas the photothermal offset signal **62** is typically a DC signal (which is either constant, or varying slowly).

[0088] The cantilever **5** is illuminated by separately generating the oscillation signal **63** and the photothermal offset signal **62**; combining the oscillation signal and the photothermal offset signal to generate a combined signal **66**; and illuminating the cantilever with the actuation beam **61** under control of the combined signal **66**. That is, the photothermal actuation system **60** adjusts the intensity of the actuation beam **61** on a basis of the combined signal **66**.

[0089] In this example the oscillation signal **63** and the photothermal offset signal **63** are combined by adding them together at an adder **67**. Alternatively the oscillation signal **63** and the photothermal offset signal **62** may be combined by a different type of combiner.

[0090] A feedback control system, described in detail below, is configured to generate the photothermal offset signal **62** as a separate signal from the oscillation signal **63**.

[0091] The cantilever **5** has a thermal bimorph structure, the materials of which undergo differential expansion when heated. In one embodiment, the cantilever **5** is fabricated from silicon nitride with an aluminium coating. The photothermal actuation system **60** comprises a laser which emits the actuation beam **61** which contains light at a wavelength at which there is a maximum or peak in the absorption spectrum for the particular coating. For example the wavelength may be around the aluminium absorption peak at ~810 nm. Other coating/wavelength combinations can be used, for example gold has a higher absorption at wavelengths below 500 nm. When this light is incident on the coating side of the cantilever **5**, the aluminium expands to a greater degree than the silicon nitride, bending the cantilever such that the tip moves downwards, towards the sample. If illumination intensity is increased, the tip therefore moves closer to the sample surface. Conversely, if the intensity is lowered, bending is decreased and the tip is moved away from the sample. Other arrangements of coating and base materials may result in different levels of bending in the same or opposite direction in response to illumination.

[0092] As explained above, the detection beam **32** of FIG. **2** is directed onto the cantilever by a steering mirror **33** and an objective lens **37**. As the steering mirror **33** tilts, the reflected detection beam **32** deflects and retains its position on the distal end of the cantilever **5**.

[0093] The actuation beam **61** is also directed onto the cantilever by the steering mirror **33** and the objective lens **37**. As the steering mirror **33** tilts, the actuation beam **61** deflects and retains its position on the cantilever **5** (in this case towards the proximal end of the cantilever).

[0094] Thus the steering mirror **33** retains the positions of both beams **32**, **61** on the cantilever **5**. The steering mirror **33** is driven by steering signals **65** from the scan controller **11**.

[0095] A feedback control system **70**, **80**, **81** is configured to adjust the photothermal offset signal **62** and the height control signal **21** on a basis of the height measurement signal **116**, so that the probe tip follows the topography of the sample **2**.

[0096] The feedback control system comprises an oscillation error detector configured to monitor the height measurement signal **116** to obtain an oscillation parameter **71** and generate an oscillation error signal **73** based on the oscillation parameter and an oscillation parameter setpoint.

[0097] In this example, the oscillation parameter is an amplitude **71** measured by an amplitude detector **70**, and the oscillation parameter setpoint is an amplitude setpoint. In other examples the oscillation parameter may be a phase or frequency

[0098] The amplitude setpoint is subtracted from the amplitude **71** to generate the oscillation error signal, which in this case is an amplitude error signal **73**. The feedback control system is configured to adjust the height control signal **21** and the photothermal offset signal **62** on a basis of this amplitude error signal **73**, as described below.

[0099] The feedback control system comprises a first feedback controller **80** configured to adjust the photothermal offset signal **62** in order to null an input to the first feedback controller **80**.

[0100] In this embodiment, the input to the first feedback controller **80** comprises the amplitude error signal **73**. Hence the first feedback controller **80** is configured to adjust the photothermal offset signal **62** so that the amplitude **71** remains at the amplitude setpoint. As a result, the photothermal offset signal **62** reacts to changes in the topography of the sample when a feature of the sample results in the amplitude error signal **73** having a non-zero value.

[0101] By way of example, the first feedback controller **80** may comprise a proportional-integral (PI) feedback controller or a proportional-integral-differential (PID) feedback controller.

[0102] A second feedback controller **81** is configured to adjust the height control signal **21** in order to null an input to the second feedback controller **81**.

[0103] The feedback control system comprises a photothermal error detector configured to generate a photothermal error signal **82** based on the photothermal offset signal **62** and a photothermal offset setpoint; and the input to the second feedback controller **81** comprises this photothermal error signal **82**.

[0104] The photothermal offset setpoint may be subtracted from the photothermal offset signal **62** to generate the photothermal error signal **82**. The photothermal offset setpoint may be set at a mid-point of an operating range of the photothermal offset signal **62**. Hence the second feedback controller **81** is configured to adjust the height control signal **21** so that the photothermal offset signal **62** remains at the mid-point of its operating range.

[0105] In taking an image of the sample, the scanning probe microscope is operated in dynamic mode as follows. The cantilever **5** is set into resonant oscillatory motion by the oscillation signal generator **64**. Using the Z-actuator **20**, the probe tip **6** is first brought into intermittent contact with the sample **2**. Conventionally, in AFM terminology, the probe tip **6** is said to be in contact with the sample **2** when the atomic interaction force is in the repulsive regime. The probe mount **4** is lowered, moving the probe tip towards the sample **1** whilst, in this embodiment, the detection system **30** monitors the oscillating and time-varying deflection of the cantilever. When the amplitude of deflection oscillation reaches a predetermined level the movement of the probe mount **4** is stopped. This predetermined amplitude level is the amplitude setpoint for the feedback controller **80**.

[0106] As the scan progresses, the probe tip **6** moves up and down as surface height/interaction force varies. Superimposed on this surface-induced motion is a higher frequency component arising from the oscillatory motion of the cantilever driven by the oscillation signal **63**. The amplitude, phase and frequency of this oscillatory component of the probe tip's motion will all be dependent on both the oscillator settings and the interaction force between surface and probe tip. Similarly, the height of the probe tip is a superposition of a component arising from interaction with the sample surface and a second component due to probe oscillations. The amplitude, phase and frequency of the second component are affected by the probe tip's position with respect to the surface. As the scan progresses, the amplitude of the ac component of the height measurement signal **116** is monitored.

[0107] It will be appreciated that the height measurement signal **116** contains accurate information relating to the height of the probe tip, but this must be related to features of the sample surface in order for useful information to be obtained. In theory, the lowest point of each oscillation cycle represents the true height of the surface. Accordingly the signal processor **50** may be set up in order to be able to find the lowest height measurement for each period of probe oscillation and this is then output as a topography measurement signal **51** that can be used by the image collection module **52** to form an image. That is, the lowest point in each oscillation cycle is representative of the position of the sample surface.

[0108] Other points of the high-frequency oscillation component of the signal may also be used to provide a meaningful indicator of sample surface position. For example, the point of minimum velocity during the lower half of the oscillation cycle may be extracted by the data processing system. If imaging a compliant surface then the probe velocity, or equivalently rate of change of the height signal, will fall as it encounters and begins to deforms the surface. In this instance a measure of sample height may be extracted from the point of each height oscillation at which a variation in the rate of change of probe height is observed.

[0109] The signal processer **50** is preferably arranged to extract data from a position within each oscillation cycle of the height measurement signal **116** that satisfies a predetermined measurement criterion. This may be when the cycle indicates an extremal path difference, a minimum rate of change in path difference, or another suitable indicator. This ensures that the measurement point is extracted at a position most likely to reflect the true height of the sample. For example, at a minimum (or maximum) path difference it can be inferred that the probe tip is in contact with the sample surface. This improves the accuracy of information extracted by the detection system **30**, which may then be used by the image collection module **52** to generate an image of the sample surface. This image may reflect surface height, or any other aspect of the topography of the sample.

[0110] Alternatively, the signal processer **50** could use an average of the height measurement signal **116** to generate the topography measurement signal **51** which is used by the image collection module **52** to form an image.

[0111] In this example, an image collection module **52** constructs an image on the basis of the topography measurement signal **51**, and an XY position signal **55** from the scan controller **11** which indicates the current XY position of the probe tip.

[0112] In other embodiments of the invention, rather than generating an image with an image collection module **52**, the scanning probe microscope **1** may use the topography measurement signal **51** in some other way—for instance to measure a critical dimension of the sample (such as a wall height, wall angle, trench width, etc.). In this case a series of topography measurements may be measured with only a single line scan (for instance across a trench) rather than scanning in two-dimensions to generate a topographical image.

[0113] FIG. **3** gives an example of a topography of the surface of the sample **2**. In this case, the surface of the sample has a steep sidewall **90** with a height H. Sidewalls of this type are common in semiconductor samples, for instance at a sidewall of a trench or other feature.

[0114] FIG. **4** shows a scanning probe microscope **1*a*** according to a comparative example, not according to the present invention. In this case, the resonant oscillation is driven by a piezoelectric actuator **60*a*** rather than the photothermal actuation system **60** of FIG. **2**. A height actuation system **20*a*,** similar to the Z-actuator **20** of FIG. **2**, is configured to adjust a height of the proximal end of the cantilever by moving the probe mount under control of a height control signal from a PID controller. The scanning probe microscope **1*a*** is similar to the scanning probe microscope described in WO2010067129A1.

[0115] A first problem with the scanning probe microscope **1*a*** of FIG. **4** is that the piezoelectric actuator **60*a*** has a low bandwidth. As a consequence, in order to accurately image the steep sidewall **90**, the probe must be scanned slowly in the XY plane. Slow scan rates are particularly problematic in the analysis of semiconductor samples, for instance for process monitoring and control in a semiconductor fabrication plant or other high volume manufacturing facility.

[0116] A second problem is that the piezoelectric actuator **60*a*** may respond to the oscillation signal with its own resonances, which can cause undesirable characteristics in the oscillation of the cantilever.

[0117] FIG. **5** shows a scanning probe microscope **1*b*** according to a second comparative example, not according to the present invention. In this case the vertical motion of the probe is driven photothermally by a laser **60*b*** which has a higher bandwidth than the piezoelectric actuator **60*a*** (typically by a factor of 10 or more or by a factor of 100 or more) and hence can drive the probe tip down more rapidly to the bottom of the sidewall **90**.

[0118] A problem with the scanning probe microscope **1*b*** of FIG. **5** is that the photothermal actuation system **60*b*** has a small range, which may be less than the height H of the sidewall **90**. The scanning probe microscope **1*b*** of FIG. **5** also suffers from the problem of undesirable resonances in the piezoelectric actuator.

[0119] FIG. **6** shows a scanning probe microscope **1***c* according to a third comparative example, not according to the present invention.

[0120] In this case a photothermal actuator **60***c* drives both the oscillation of the probe (via an oscillation signal from an oscillation signal generator **64***c*) and the DC offset of the probe, following the profile of the sample.

[0121] The scanning probe microscope **1***c* of FIG. **6** has the same range problem as scanning probe microscope **1***b* of FIG. **5** but does has various advantages over the scanning probe microscope **1***b,* namely: the number of actuators is reduced (one actuator rather than two); and the direct drive of the cantilever results in a cleaner excitation of the cantilever, avoiding the undesirable oscillation characteristics caused by the piezoelectric actuator **60***a*.

[0122] The range problem could be solved by increasing the length of the cantilever, but this would increase its thermal mass which in turn would make it respond more slowly to photothermal heating (in other words, it would reduce the bandwidth of the photothermal actuation system).

[0123] The scanning probe microscope **1** of FIG. **1** includes the advantages of the scanning probe microscope **1***c* of FIG. **6** but addresses the range problem without reducing the bandwidth.

[0124] FIG. **3** shows the photothermal offset signal **62** as the probe scans across the sidewall **90**, from left to right. As the probe reaches the sidewall **90**, the photothermal offset signal **62** rapidly jumps at step **91** from 50% to 80%. The percentages indicate the amount of the full range of the photothermal actuation system: i.e. at 0% the cantilever **5** is unbent and at 100% the cantilever **5** is fully bent down. So in this example the height H of the sidewall represents 30% of the dynamic range of the photothermal actuation system. The full range is typically less than 1 micron, for instance approximately 100 nm.

[0125] The Z-actuator **20** has a low bandwidth, so it can only react slowly to the sudden change of height at the sidewall **90**. Hence the height control signal **21** gradually increases from 50% to 51% in an up-ramp **92**. The percentages indicate the amount of the full range of the Z-actuator **20**: i.e. at 0% the Z-actuator **20** is un-extended and at 100% the Z-actuator **20** is fully extended. In this example the height H of the sidewall represents only 1% of the dynamic range of the Z-actuator **20**. The full range is typically of the order of 10-15 micron, i.e. more than ten times greater than the range of the photothermal actuation system.

[0126] As the height control signal **21** gradually increases from 50% to 51% in the up-ramp **92**, the first feedback controller **80** causes the photothermal offset signal **62** to gradually reduce via a down-ramp **93**, counteracting the up-ramp **92**, until the photothermal offset signal **62** returns to its setpoint (in this case, 50%). Hence the feedback control system of the scanning probe microscope **1** addresses the range problem by ensuring that the photothermal offset signal **62** remains close to its setpoint.

[0127] FIG. **7** shows a scanning probe microscope **1***d* according to an alternative embodiment of the invention. Most elements of the scanning probe microscope **1***d* are identical to the scanning probe microscope **1** of FIG. **1**, and these elements are given the same reference number.

[0128] In the scanning probe microscope **1***d,* the input to the second feedback controller **81** comprises the amplitude error signal **73**, which is fed in parallel to the first and second feedback controllers **80**, **81**. In the scanning probe microscope **1***d,* the second feedback controller **81** operates at a slower rate than the first feedback controller **80**.

[0129] Operating the second feedback controller **81** at a lower rate than the first feedback controller **80** (or equivalently with a longer response time or a lower bandwidth) avoids unwanted interaction between the controllers **80**, **81**.

[0130] A preferred way of avoiding unwanted interaction between the feedback controllers **80**, **81** is for them to operate over non-overlapping frequency bands. For example the second feedback controller **81** may operate over a band of DC up to 1 kHz, and the first feedback controller **80** may operate over a band from a few kHz to several MHz.

[0131] Another way of avoiding unwanted interaction between the controllers **80**, **81** is for them to operate by different control methods. For example the second feedback controller **81** may be replaced by a feedforward controller.

[0132] In the alternative embodiment shown in FIG. **7**, the second feedback controller **81** receives the amplitude error signal **73** and processes this signal to provide the height control signal **21**. Therefore this embodiment does not require the photothermal offset signal **62** to be input into the second feedback controller **81**. The advantage of this embodiment is that the height control signal **21** is generated based more directly on the amplitude error signal **73**, which in turn is directly derived from the height measurement signal **116**. Also, the height control signal **21** is generated without using the first feedback controller **80**, so the system is more robust.

[0133] FIG. **8** shows a scanning probe microscope **1***e* according to a further alternative embodiment of the invention. Most elements of the scanning probe microscope **1***e* are identical to the scanning probe microscope **1***d* of FIG. **7**, and these elements are given the same reference number.

[0134] In FIG. **8**, the detection system **30***a* comprises a differential interferometer which is similar to the interferometer **105** of FIG. **2** in that it illuminates the probe with a detection beam **32** which is steered onto the distal end of the cantilever **5** by a steering mirror **33**. In this case the reference beam **39** is steered onto the proximal end of the cantilever **5** (or onto the probe mount **4**) by the steering mirror **33** to generate a reflected reference return beam which is combined with the reflected detection return beam from the distal end of the cantilever. Hence the differential interferometer generates an output which indicates the height difference between the proximal end of the cantilever **5** (or the probe mount **4**) and the distal end of the cantilever. So the output of the detection system **30***a* is a signal **116***a* which is indicative of a height of the distal end of the cantilever (relative to the proximal end rather than a fixed reference frame), and is also indicative of probe deflection.

[0135] The signal **116***a* from the detection system **30***a* is combined with the height control signal **21** at the signal processor **50** to determine the sample height and hence provide a topography measurement.

[0136] FIG. **9** shows a scanning probe microscope **1***f* according to a further alternative embodiment of the invention. Most elements of the scanning probe microscope **1***f* are identical to the scanning probe microscope **1***d* of FIG. **7**, and these elements are given the same reference number.

[0137] The cantilever **5** has a fundamental eigenmode with a fundamental eigenmode frequency (denoted f1) and one or more higher-order eigenmodes each having a frequency (denoted f2, f3 etc) higher than the fundamental eigenmode frequency. In the previous embodiments, the oscillation signal **63** excites the fundamental eigenmode. In the case of FIG. **9**, the oscillation signal **63** excites one of the higher-order eigenmodes, in this case the second eigenmode (with a frequency denoted f2). Hence the oscillation signal **63** is a sinusoidal signal with a frequency f2.

[0138] FIG. **9** also incorporates a bandpass filter **75** which is tuned to pass the frequency f2 of the higher-order eigenmode and block other frequencies (including the frequency f1 of the fundamental eigenmode); and a bandpass filter **76** which is tuned to pass the frequency f1 of the fundamental eigenmode and block other frequencies (including the frequency f2 of the higher-order eigenmode).

[0139] A Q-control module **77** applies a Q-control signal to the combined signal **66** to damp oscillation of the cantilever **5** at the frequency f1 of the fundamental eigenmode. The Q-control signal is based on the bandpass filtered height measurement signal output by the bandpass filter **76**, with an appropriately adjusted phase and gain.

[0140] The Q-control module **77** may damp oscillation of the cantilever using a similar method to the Q-control method implemented in NPL [5] (Balantekin et al). Note that NPL [5] applies Q-control to a regular cantilever which is not photothermally actuated. Alternative methods of Q-control which may be implemented by the Q-control module **77** are described in NPL [6] (Mertz et al) and NPL [7] (Ruppert et al). NPL [6] and NPL [7] apply Q-control to a photothermally actuated cantilever.

[0141] The oscillation signal generator **64** in FIG. **9** is configured to generate and output the oscillation signal **63** at the frequency f2, so it excites oscillation of the cantilever according to the second eigenmode.

[0142] The bandpass filter **75** is configured to filter the measurement signal by passing the frequency f2 of the higher-order eigenmode and blocking the frequency f1 of the fundamental eigenmode, thereby producing a filtered measurement signal **78**. The amplitude detector **70** receives this filtered measurement signal **78** as an input, so the photothermal offset signal **62** and the height control signal **21** are both adjusted by the control system on a basis of the filtered measurement signal **78**.

[0143] FIG. **10** shows a scanning probe microscope **1***g* according to a further alternative embodiment of the invention. Most elements of the scanning probe microscope **1** are identical to the scanning probe microscope **1** of FIG. **1**, and these elements are given the same reference number. Other elements of the scanning probe microscope **1***g* are identical to the scanning probe microscope **1***f* of FIG. **9**, and again these elements are given the same reference number.

[0144] In FIG. **10** (as in FIG. **1**) the microscope has a nested feedback arrangement in which the output of the PID controller **80** feeds into the PID controller **81**. As in FIG. **9**, the oscillation signal **63** excites one of the higher-order eigenmodes, in this case the second eigenmode (with a frequency denoted f2).

[0145] The principal of FIG. **9** or FIG. **10** may be extended further such that the oscillation signal **63** excites an even higher-order eigenmode, such as the third eigenmode, the fourth eigenmode, etc. In this case the frequency of the bandpass filter **75** is adapted accordingly to match the frequency of the higher-order eigenmode, and one or more further Q-control modules are added so that each lower eigenmode is damped for the purpose of Q-control. Thus, for example, if the oscillation signal **63** excites the third eigenmode (frequency f3) then a second (f2) Q-control module and bandpass filter are added so that two Q-control signals (at frequencies f1 and f2) are applied to the combined signal **66**.

[0146] In summary, the embodiments of the present invention described above provide a feedback control system comprising a pair of feedback controllers **80**, **81** each configured to adjust a photothermal offset signal and a height control signal on a basis of a respective input which is derived (directly or indirectly) from a height measurement signal **116**, **116***a*. The first feedback controller **80** may be configured to adjust the photothermal offset signal on a basis of an oscillation error signal which is derived directly from the height measurement signal **116**, **116***a*. The second feedback controller **81** may be configured to adjust the height control signal on a basis of either a photothermal error signal (which is derived indirectly from the height measurement signal **116**, **116***a*) or on a basis of the oscillation error signal (which is derived directly from the height measurement signal **116**, **116***a*).

[0147] In other embodiments of the invention (not shown) the first feedback controller **80** could be replaced by a first feedforward controller which uses feedforward information from a previous line scan combined with feedback from the amplitude or sample interaction signal. The second feedback controller **81** could be replaced by a second feedforward controller which completely operates on feedforward information from the previous scan line or a combination.

[0148] In the embodiments above, the detection system **30** comprises an interferometer **105** shown in FIG. **2**, which is configured to measure a height of the distal end of the cantilever **5** to generate a height measurement signal **116**. This height measurement signal **116** is used to obtain the topography measurements and to control the actuation system. That is, the signal processor **50** is configured to monitor the height measurement signal **116** to obtain a series of topography measurements indicative of a topography of the sample; and the control system **80**, **81** is configured to adjust the photothermal offset signal **62** and the height control signal **21** on a basis of the height measurement signal **116**.

[0149] In the cases of FIGS. **1**, **7**, **9** and **10** an alternative type of detection system (such as an optical lever) may be used instead which does not use interferometry to measure the distal end of the cantilever, but generates a measurement signal in a different way.

[0150] The detection system **30** of FIG. **2** incorporates an optical lever-based detection system which reflects a detection beam off the distal end of the cantilever and then directs the reflected beam onto a split photodiode **104**. The optical lever measures the deflection angle of the distal end of the cantilever, rather than directly measuring its height.

[0151] In these alternative embodiments, the deflection measurement signal **117** may be used in a similar way to the height measurement signal **116**. Hence (for example) the signal processor **50** may be configured to monitor the deflection measurement signal **117** to obtain a series of topography measurements indicative of a topography of the sample; and the control system **80**, **81** may be configured to adjust the photothermal offset signal **62** and the height control signal **21** on a basis of the deflection measurement signal **117**.

[0152] Although the invention has been described above with reference to one or more preferred embodiments, it will be appreciated that various changes or modifications may be made without departing from the scope of the invention as defined in the appended claims.

1. A scanning probe microscope configured to measure a topography of a sample, the scanning probe microscope comprising: a probe mount; a cantilever carried by the probe mount, the cantilever extending from a proximal end at the probe mount to a distal end remote from the probe mount; a probe tip at the distal end of the cantilever; a scanning system configured to generate a relative scanning motion between the probe mount and the sample; a detection system configured to measure the distal end of the cantilever to generate a measurement signal; a signal processor configured to monitor the measurement signal to obtain a series of topography measurements indicative of a topography of the sample; a height actuation system configured to adjust a height of the proximal end of the cantilever by moving the probe mount under control of a height control signal; a photothermal actuation system configured to bend the cantilever by illuminating the cantilever with an actuation beam under control of a photothermal offset signal and an oscillation signal; an oscillation signal generator configured to generate the oscillation signal; and a control system configured to adjust the photothermal offset signal and the height control signal on a basis of the measurement signal.

2. A scanning probe microscope according to claim **1** wherein the control system comprises an oscillation error detector configured to monitor the measurement signal to obtain an oscillation parameter and generate an oscillation error signal based on the oscillation parameter and an oscillation parameter setpoint; and wherein the control system is configured to adjust the photothermal offset signal and the height control signal on a basis of the oscillation error signal.

3. A scanning probe microscope according to any claim **1**, wherein the control system comprises: a first feedback controller configured to adjust the photothermal offset signal in order to null an input to the first feedback controller; and a second feedback controller configured to adjust the height control signal in order to null an input to the second feedback controller.

4. A scanning probe microscope according to claim **2**, wherein the control system comprises: a first feedback controller configured to adjust the photothermal offset signal in order to null an input to the first feedback controller; and a second feedback controller configured to adjust the height control signal in order to null an input to the second feedback controller, wherein the input to the first feedback controller comprises the oscillation error signal.

5. A scanning probe microscope according to claim **3**, wherein the control system further comprises a photothermal error detector configured to generate a photothermal error signal based on the photothermal offset signal and a photothermal offset setpoint; and the input to the second feedback controller comprises the photothermal error signal.

6. A scanning probe microscope according to claim **5**, wherein the photothermal offset setpoint is at a mid-point of an operating range of the photothermal offset signal.

7. A scanning probe microscope according to claim **2**, wherein the control system comprises: a first feedback controller configured to adjust the photothermal offset signal in order to null an input to the first feedback controller; and a second feedback controller configured to adjust the height control signal in order to null an input to the second feedback controller, wherein the input to the second feedback controller comprises the oscillation error signal.

8. A scanning probe microscope according to claim **4**, wherein the input to the second feedback controller comprises the oscillation error signal.

9. A scanning probe microscope according to claim **1**, wherein the oscillation signal causes the cantilever to bend in a series of oscillation cycles, and the signal processor is configured to obtain a topography measurement indicative of the topography of the sample for each oscillation cycle.

10. A scanning probe microscope according to claim **1**, wherein the signal processor is configured to monitor the height signal and to derive a measurement for each oscillation cycle that is indicative of the height of the probe.

11. A scanning probe microscope according to claim **1**, wherein the photothermal actuation system has a higher bandwidth than the height actuation system.

12. A scanning probe microscope according to claim **1**, wherein the height actuation system has a larger range of motion than the photothermal actuation system.

13. A scanning probe microscope according to claim **1**, wherein the control system comprises: a first controller configured to adjust the photothermal offset signal; and a second controller configured to adjust the height control signal.

14. A scanning probe microscope according to claim **1**, wherein the control system is configured to adjust the photothermal offset signal to respond to changes in the topography of the sample.

15. A scanning probe microscope according to claim **1**, further comprising a combiner configured to combine the oscillation signal and the photothermal offset signal to generate a combined signal, wherein the photothermal actuation system is configured to illuminate the cantilever with the actuation beam under control of the combined signal.

16. A method of measuring a topography of a sample with a scanning probe microscope according to claim **1**, the method comprising: generating a relative scanning motion between the probe mount and the sample with the scanning system; measuring the distal end of the cantilever with the interferometer to generate a measurement signal; monitoring the measurement signal with the signal processor to obtain a series of topography measurements indicative of the topography of the sample; adjusting a height of the proximal end of the cantilever with the height actuation system by moving the probe mount under control of a height control signal; generating an oscillation signal with the oscillation signal generator; bending the cantilever with the photothermal actuation system by illuminating the cantilever with an actuation beam under control of a photothermal offset signal and the oscillation signal; and adjusting the photothermal offset signal and the height control signal with the control system on a basis of the measurement signal.

17. A method according to claim **16**, wherein the cantilever has a fundamental eigenmode with a fundamental eigenmode frequency, and one or more higher-order eigenmodes each having a frequency higher than the fundamental eigenmode frequency, and wherein the oscillation signal excites one of the higher-order eigenmodes.

18. A scanning probe microscope according to claim **1**, wherein the cantilever has a fundamental eigenmode with a fundamental eigenmode frequency, and one or more higher-order eigenmodes each having a frequency higher than the fundamental eigenmode frequency, and wherein the oscillation signal excites one of the higher-order eigenmodes.

19. A scanning probe microscope according to claim **18**, further comprising a Q-control module configured to apply a Q-control signal to the actuation beam to damp oscillation of the cantilever at the fundamental eigenmode frequency.

20. A scanning probe microscope according to claim **18**, further comprising a filter which is configured to filter the measurement signal by passing the frequency of the higher-order eigenmode and blocking other frequencies, thereby producing a filtered measurement signal, wherein the photothermal offset signal and the height control signal are adjusted by the control system on a basis of the filtered measurement signal.

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