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(54) **MAGNETIC ACTUATION AND THERMAL CANTILEVERS FOR TEMPERATURE AND FREQUENCY DEPENDENT ATOMIC FORCE MICROSCOPY**

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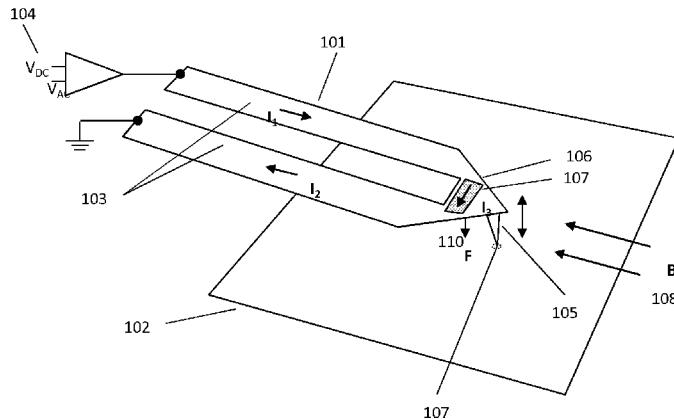
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(57) **ABSTRACT**

Described are methods for magnetically actuating microcantilevers and magnetically actuated and self-heated microcantilevers. Also described are methods for determining viscoelastic properties and thermal transition temperatures of materials.

26 Claims, 37 Drawing Sheets



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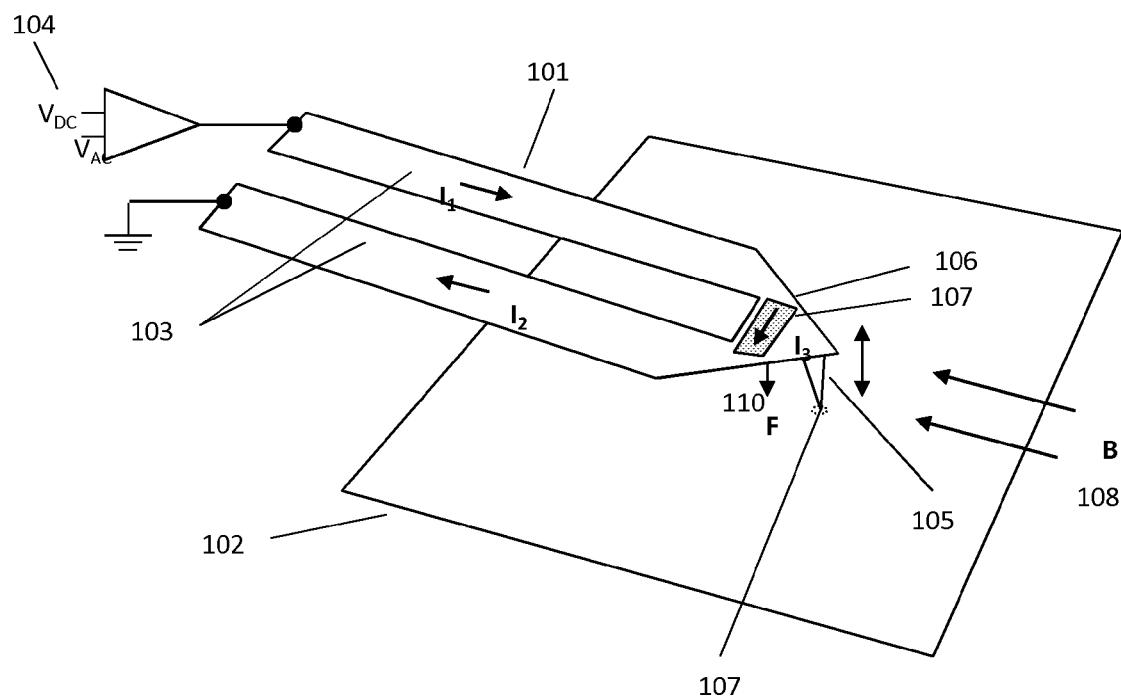
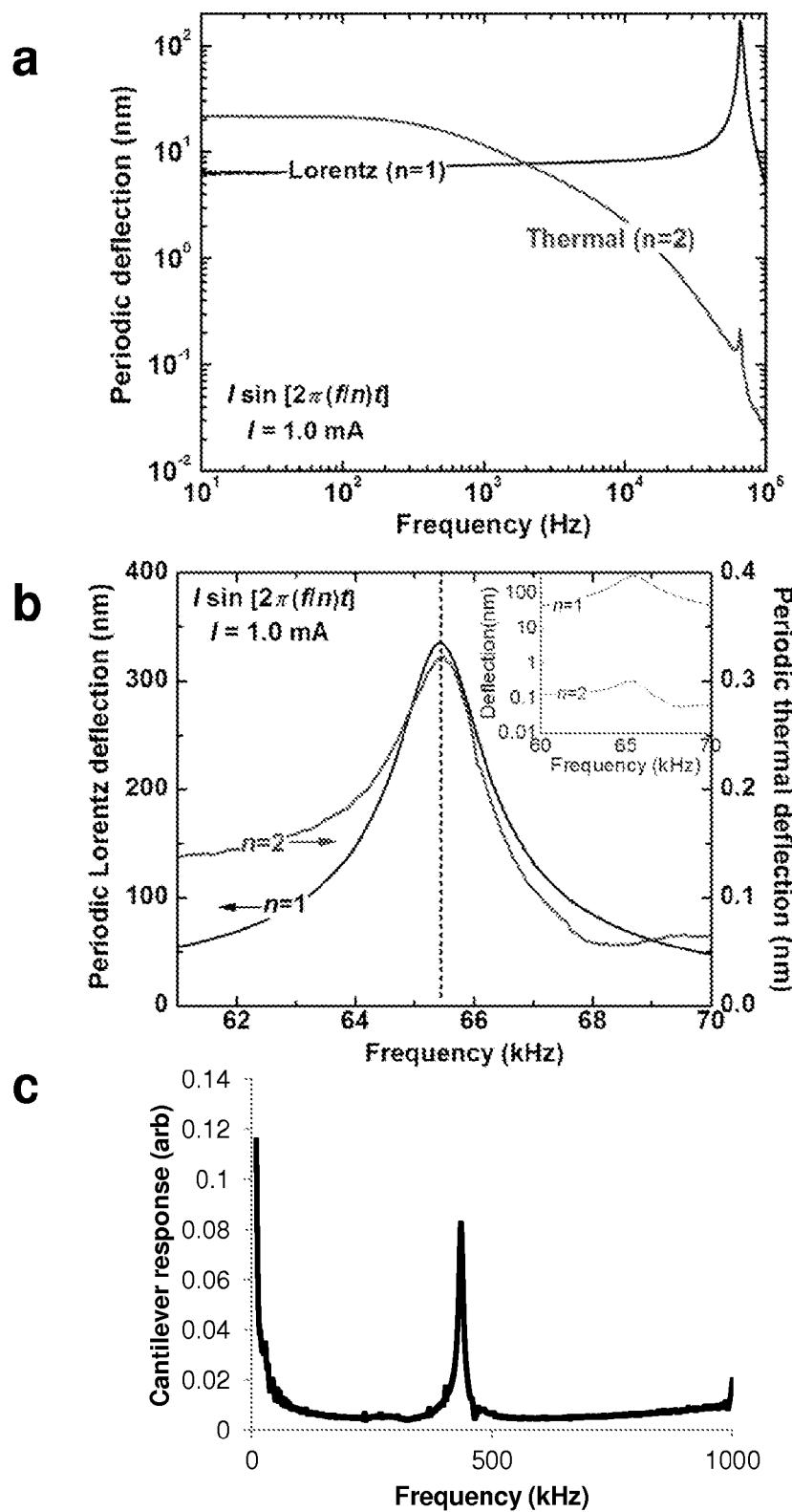


Figure 1

**Figure 2**

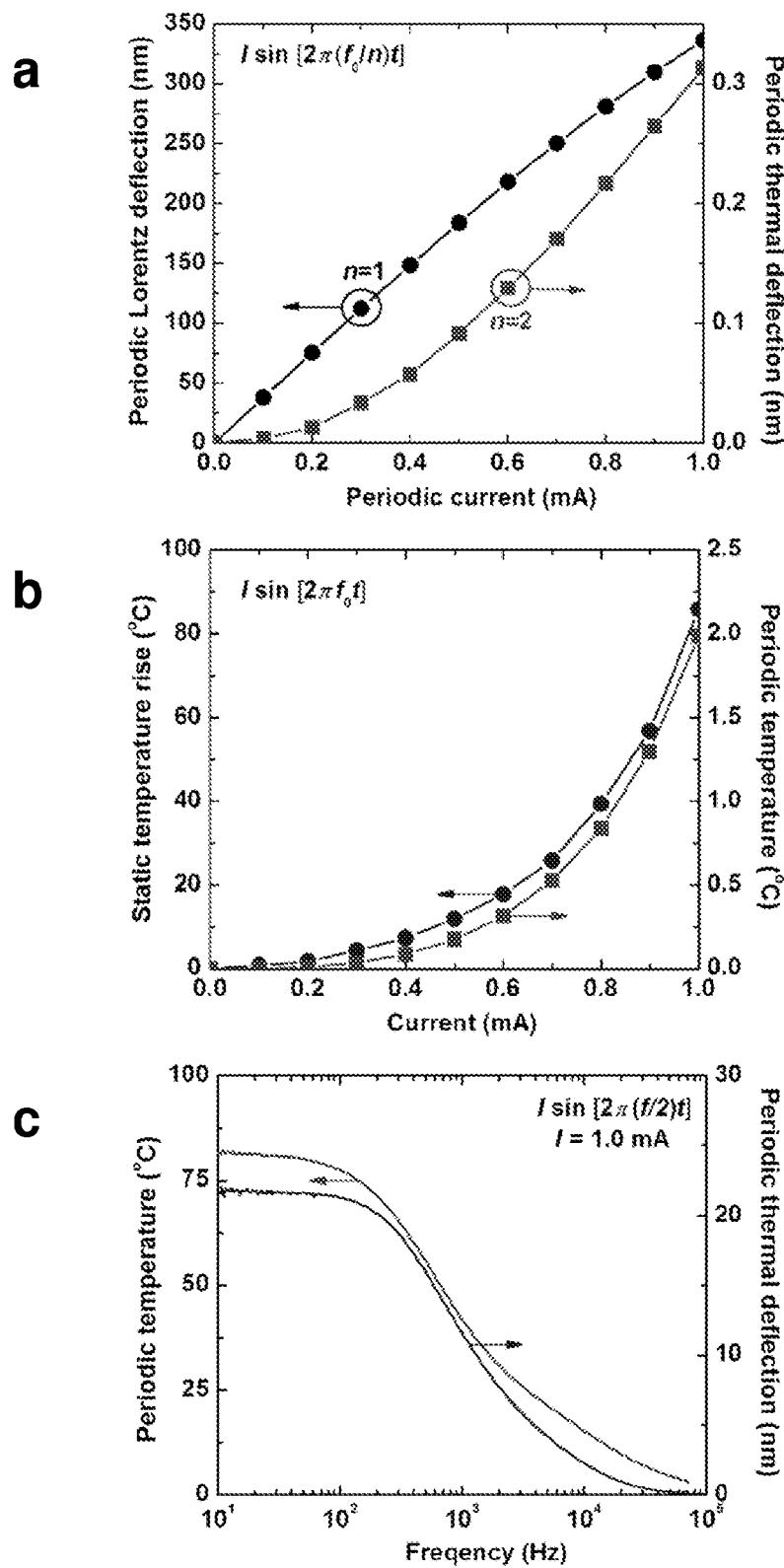


Figure 3

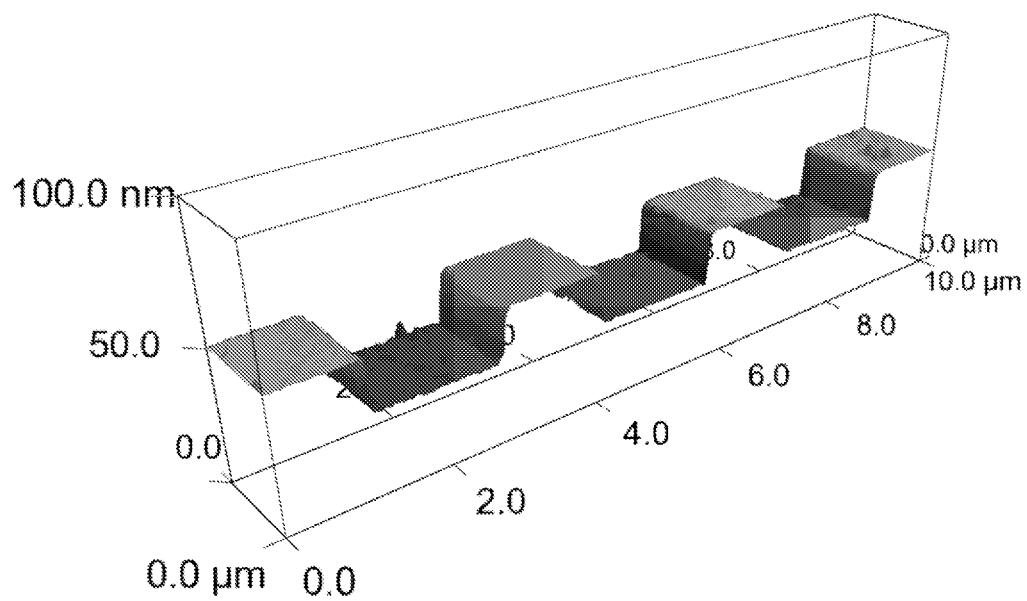
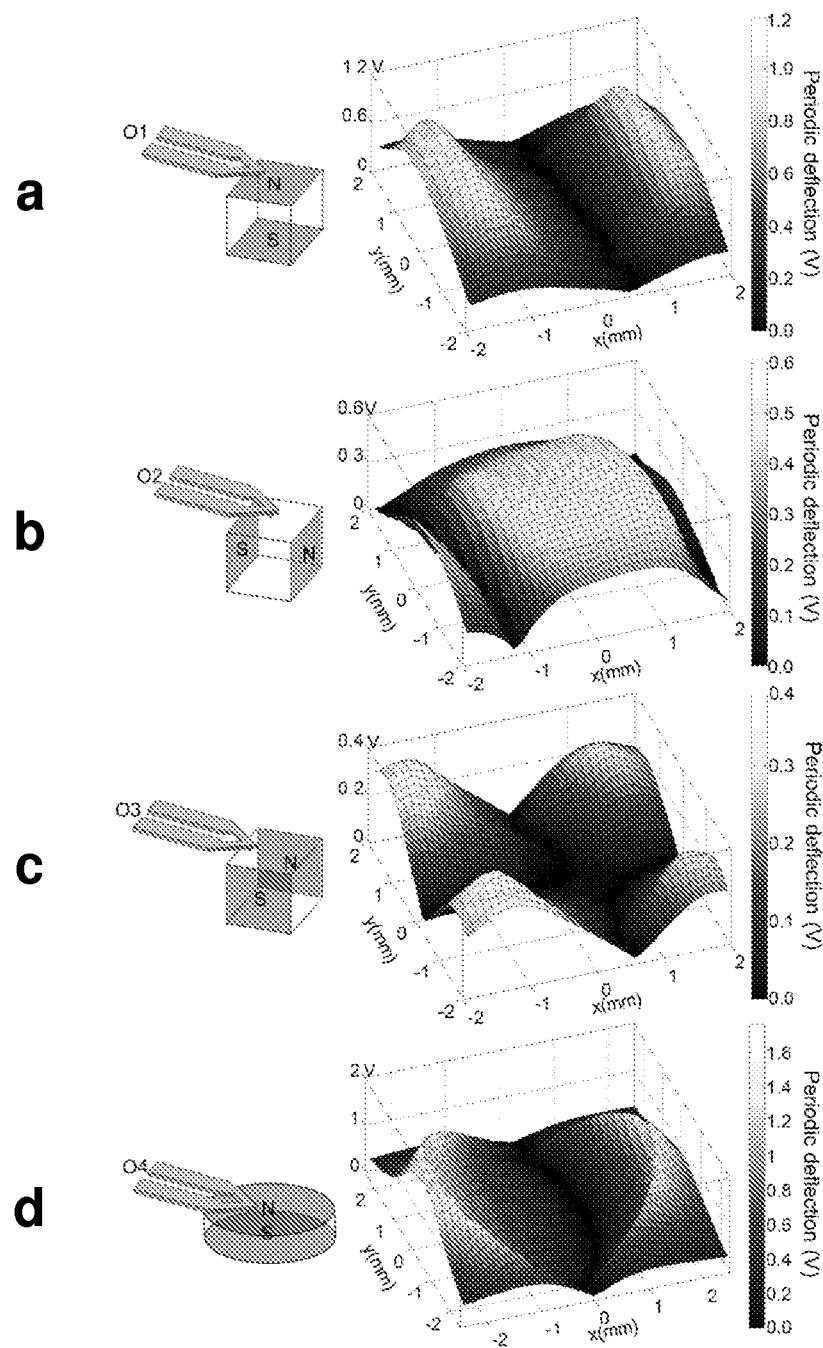


Figure 4

**Figure 5**

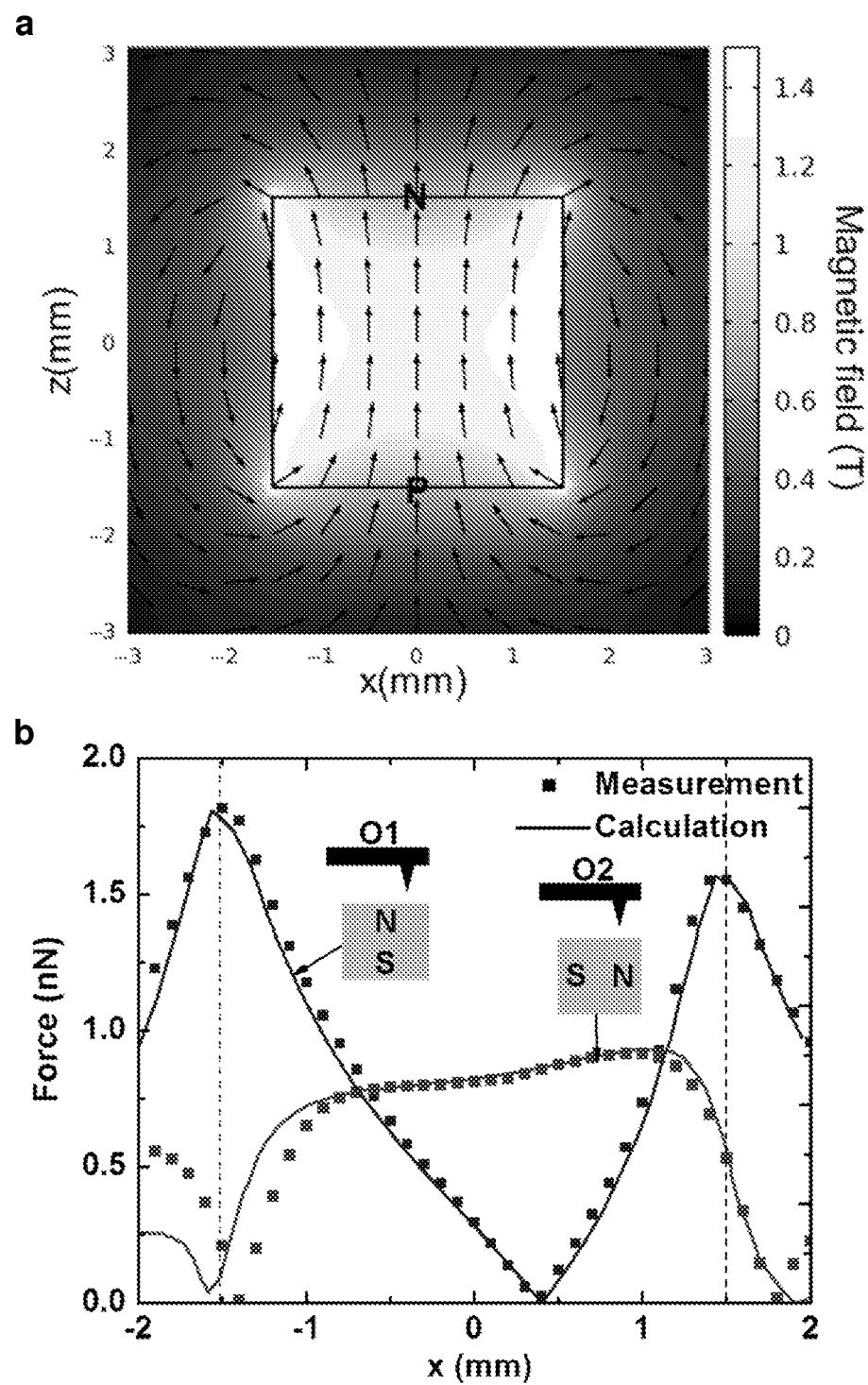
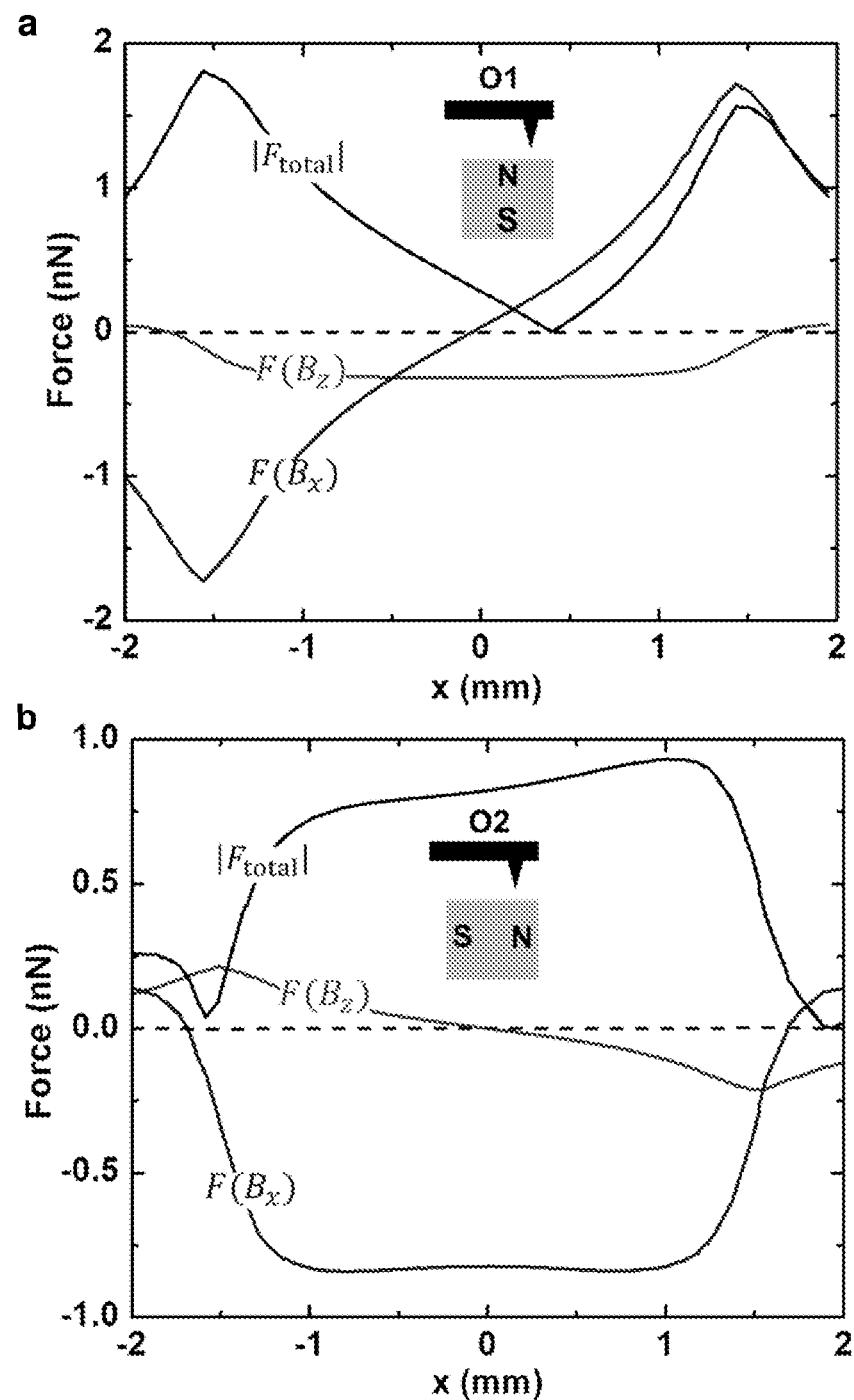


Figure 6

**Figure 7**

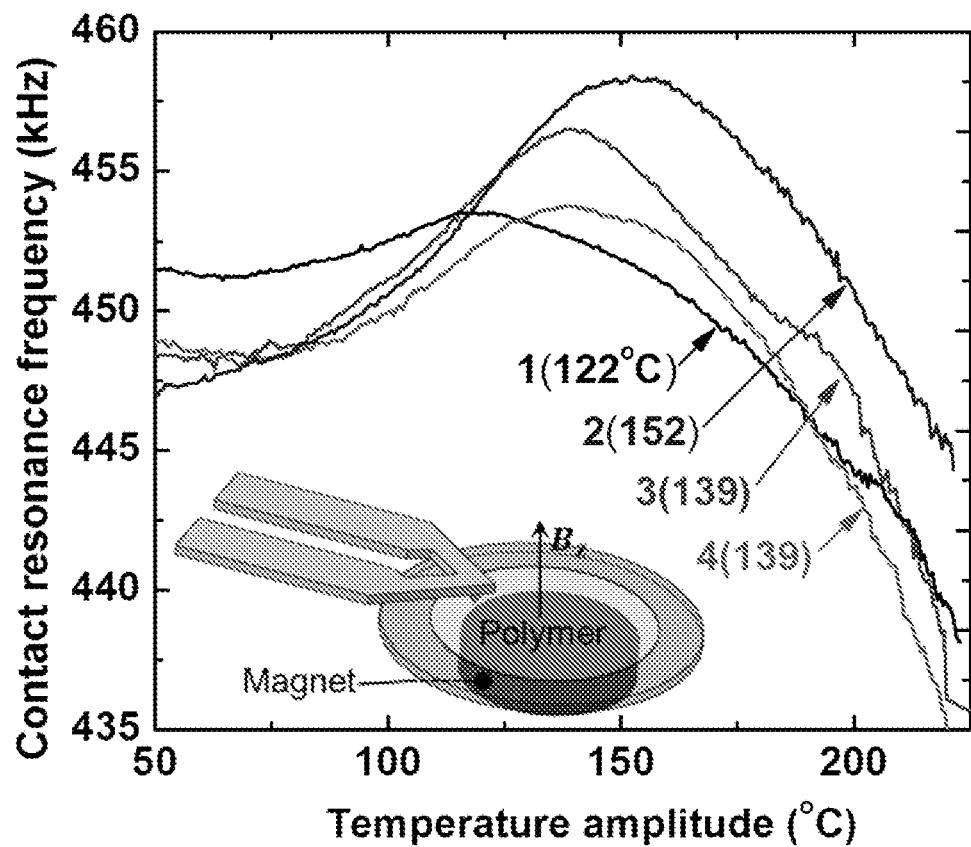
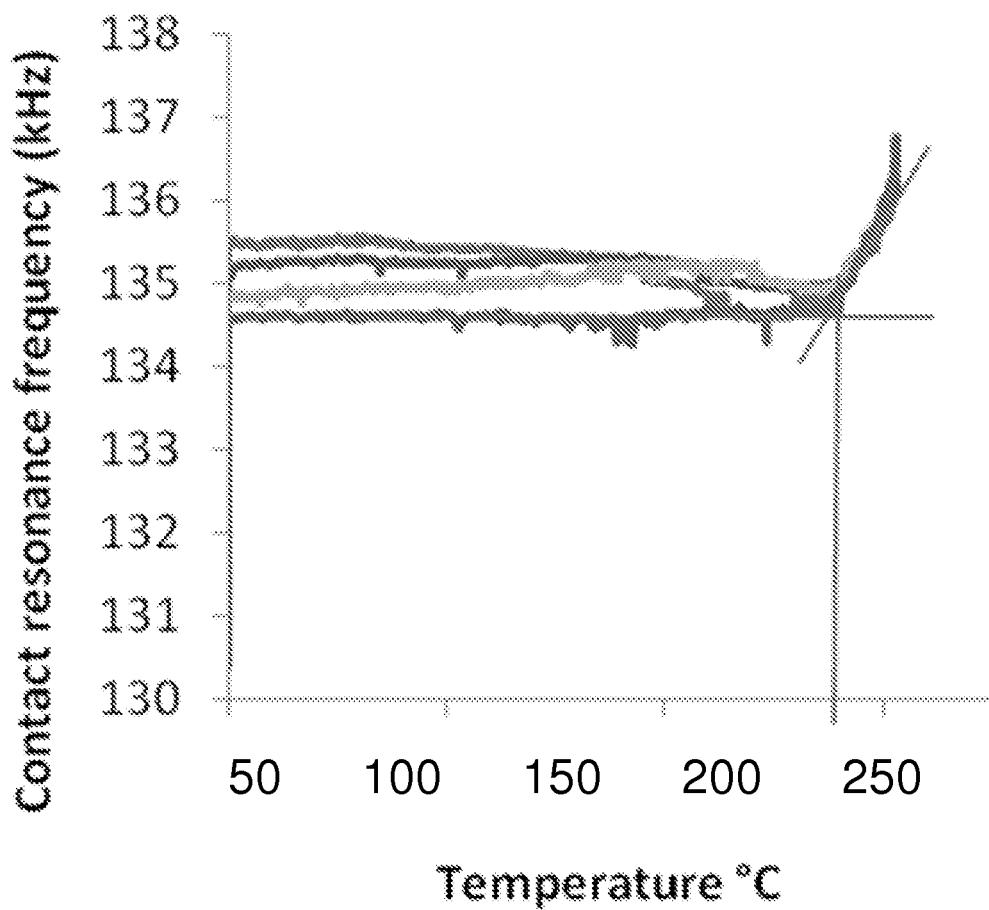


Figure 8

**Figure 9**

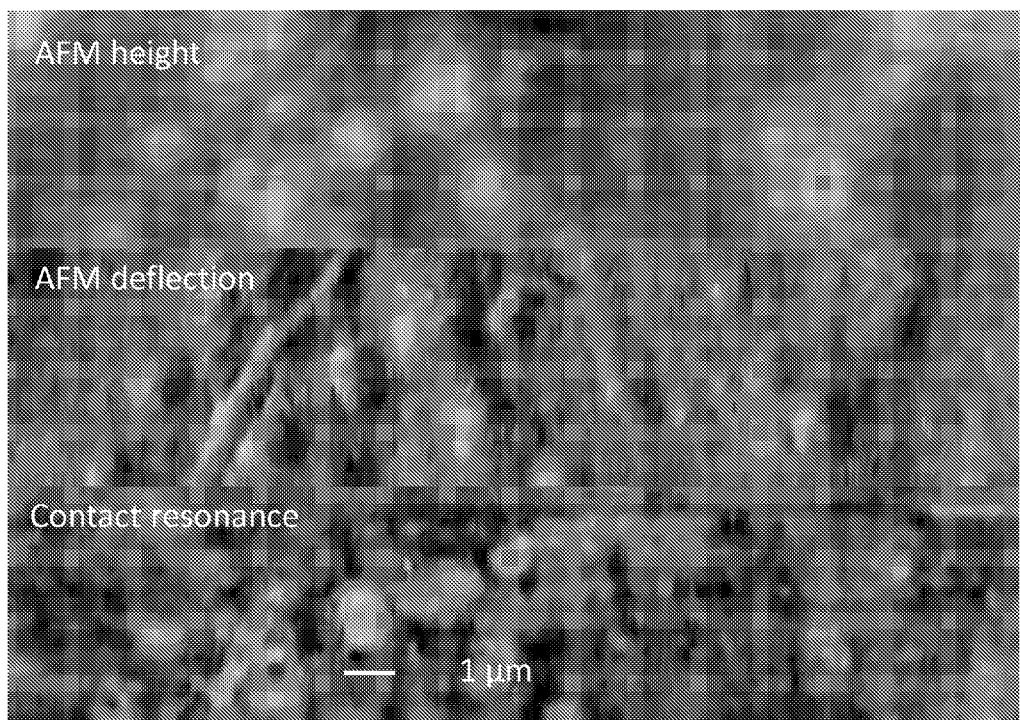
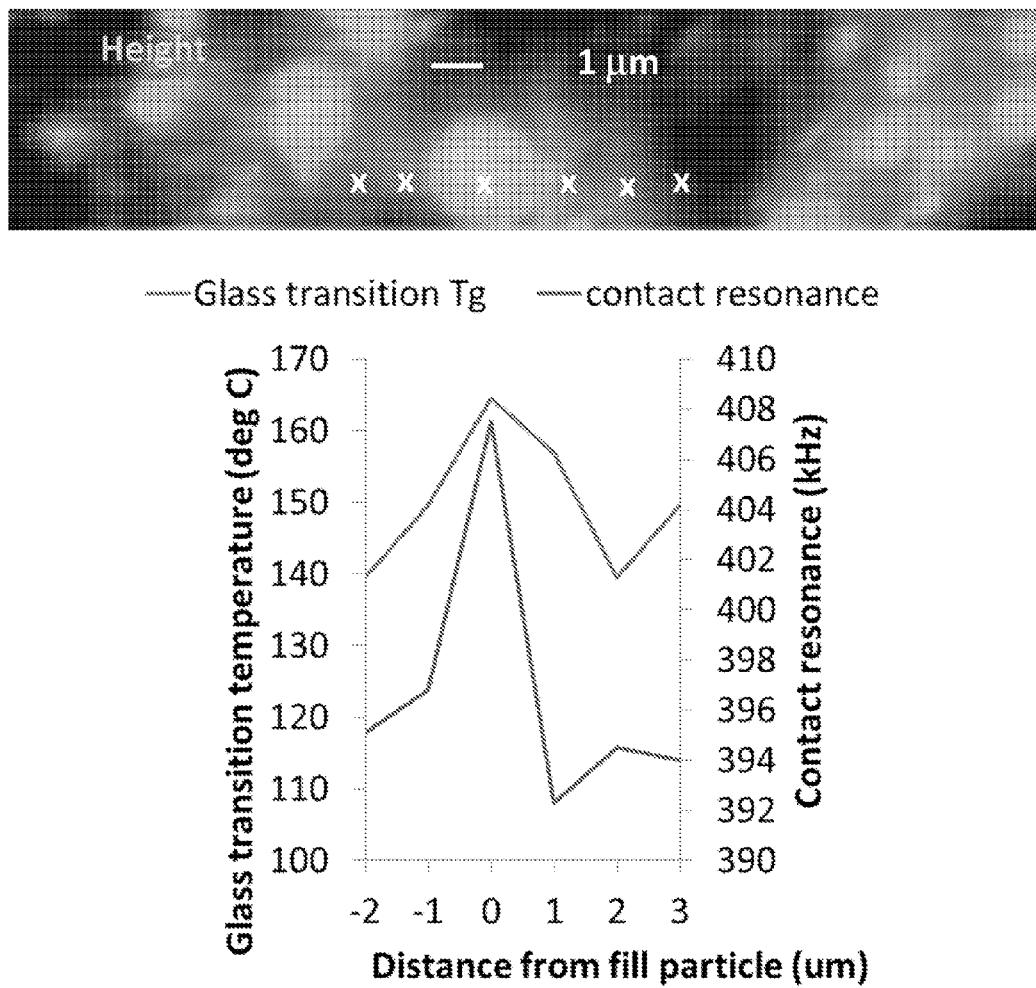


Figure 10

**Figure 11**

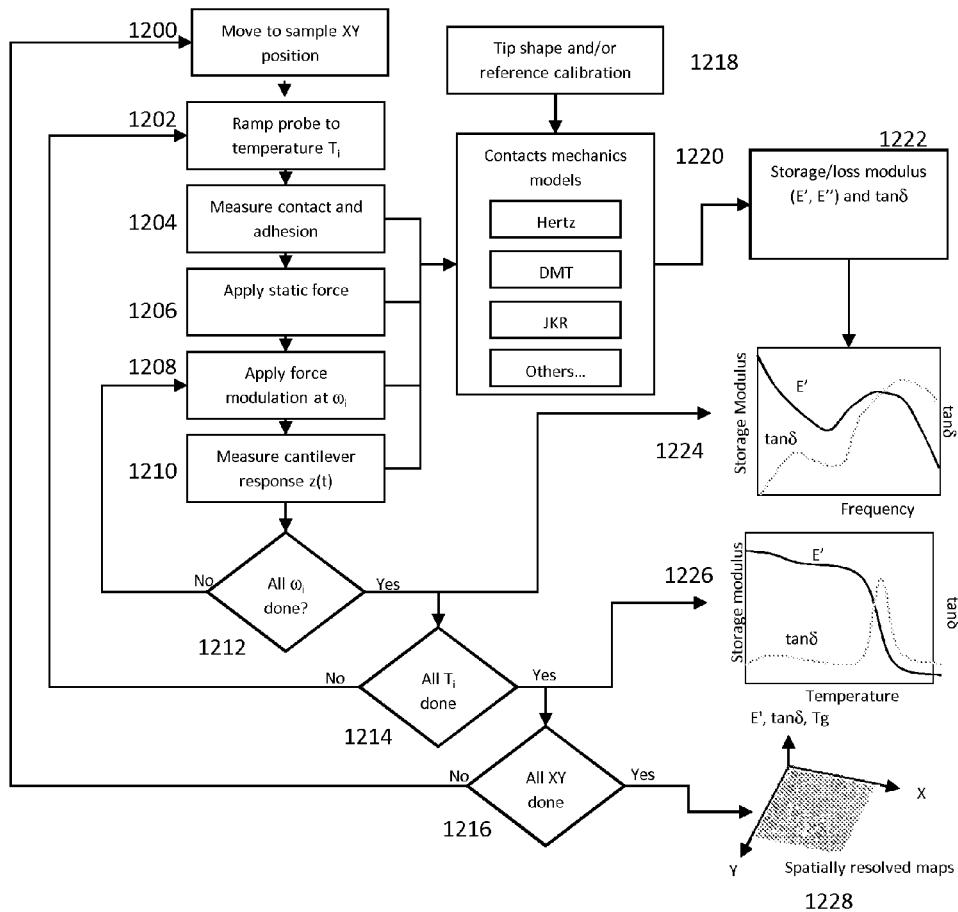
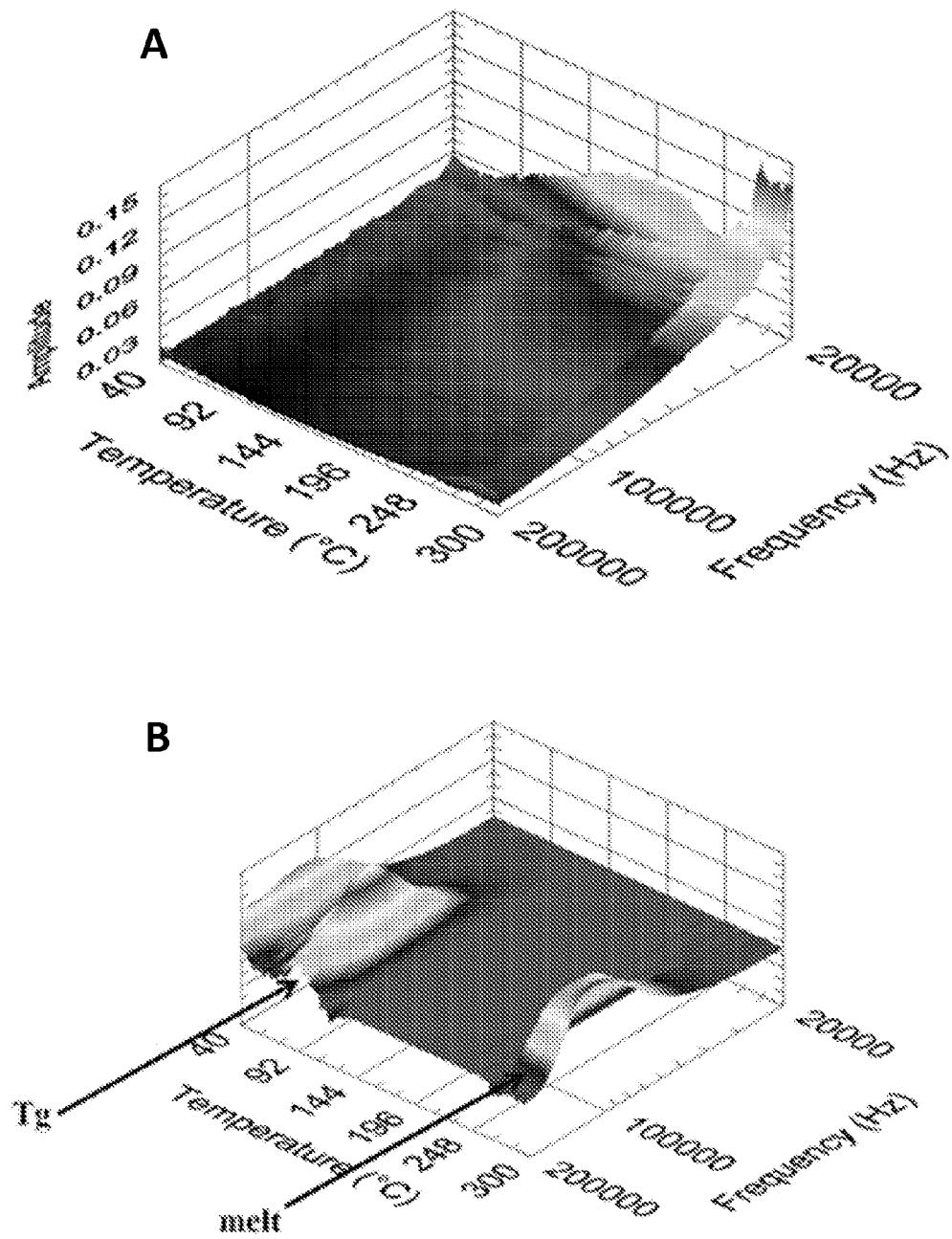


Figure 12

**Figure 13**

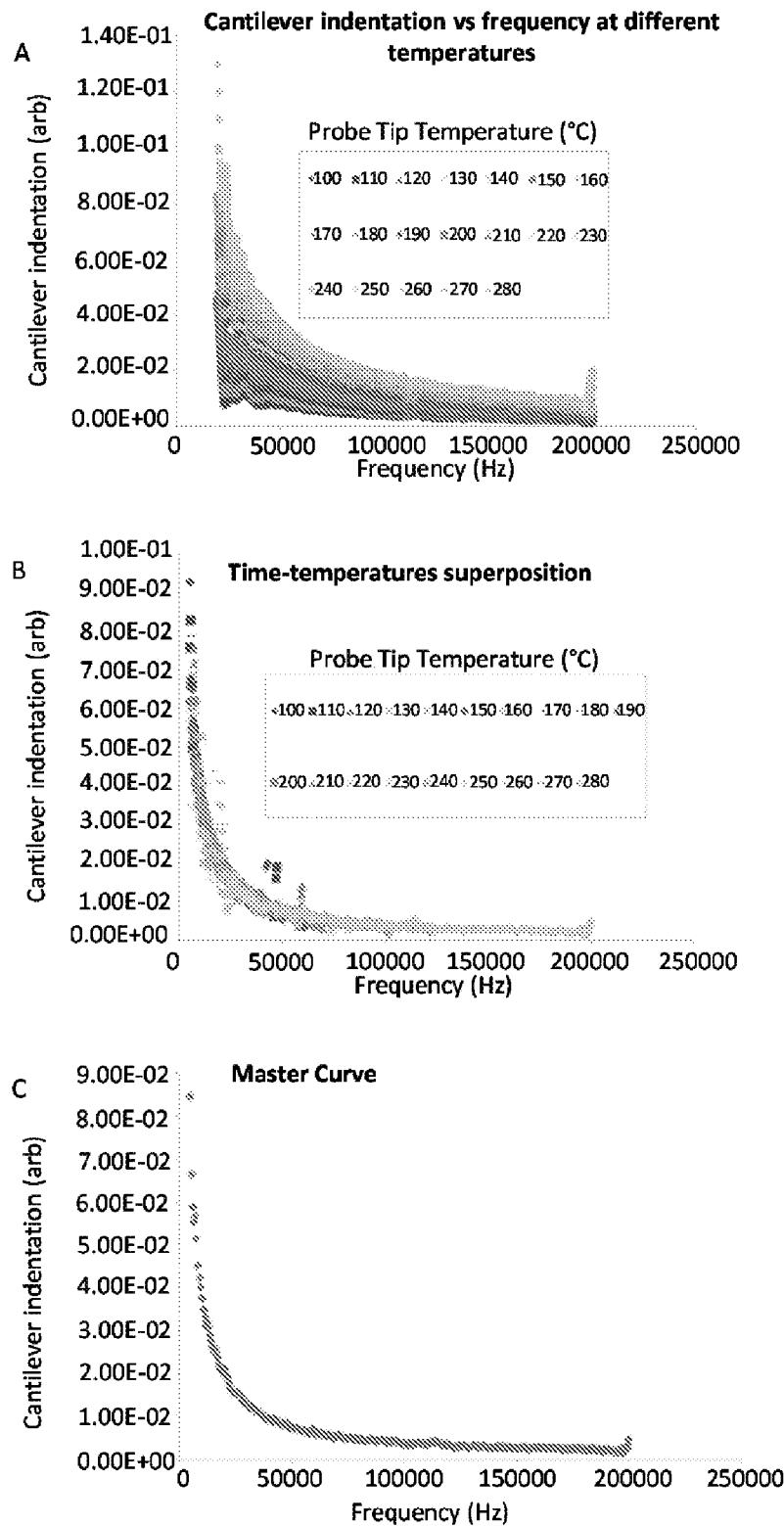


Figure 14

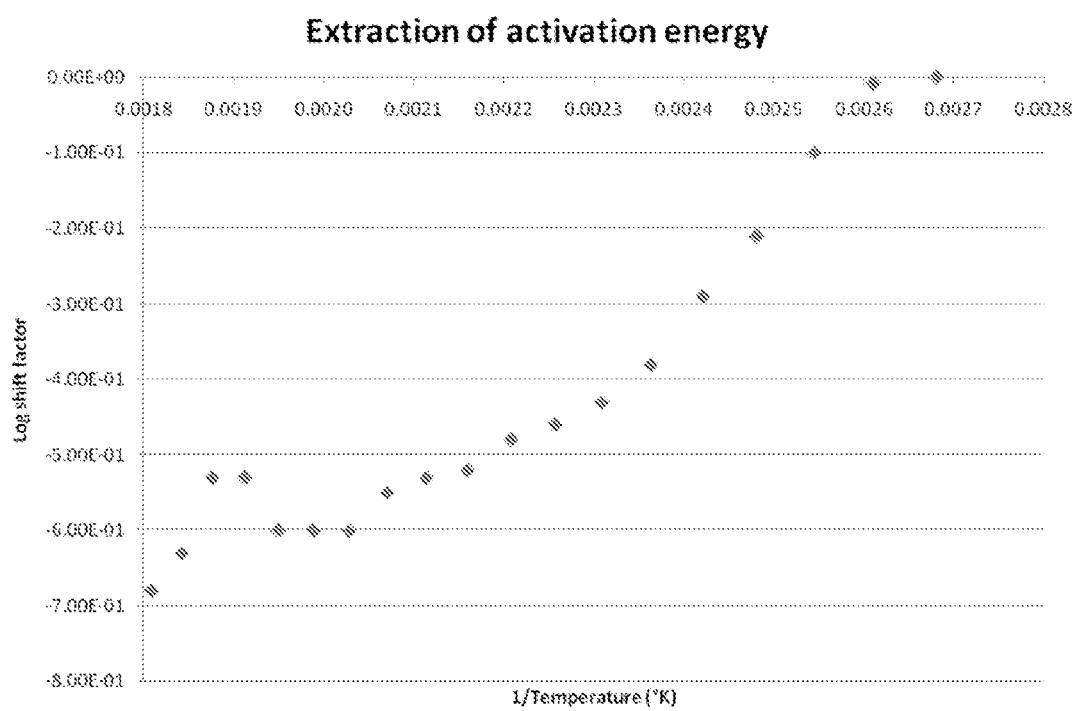


Figure 15

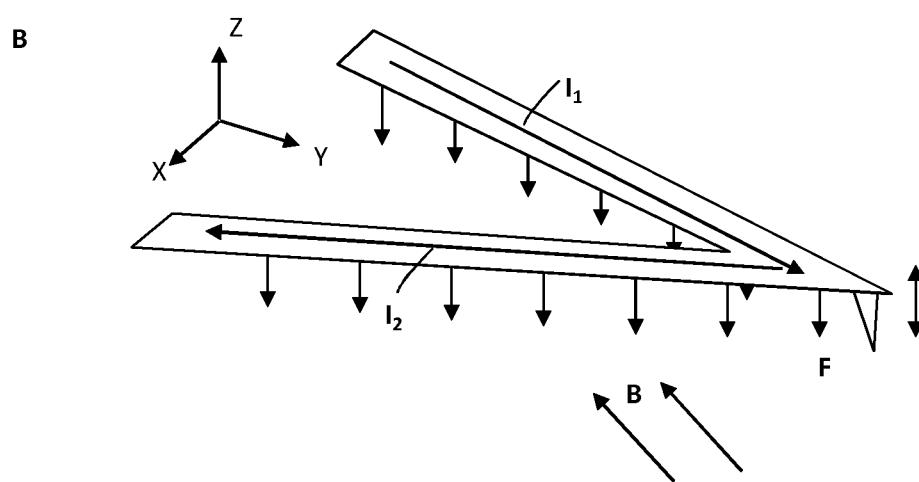
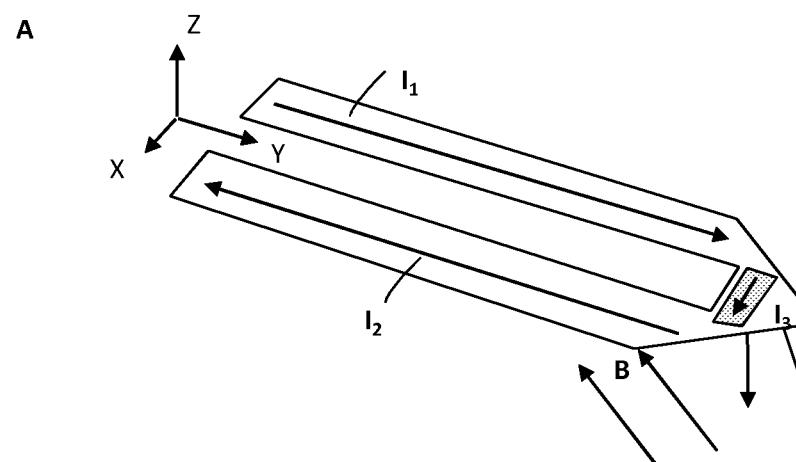


Figure 16

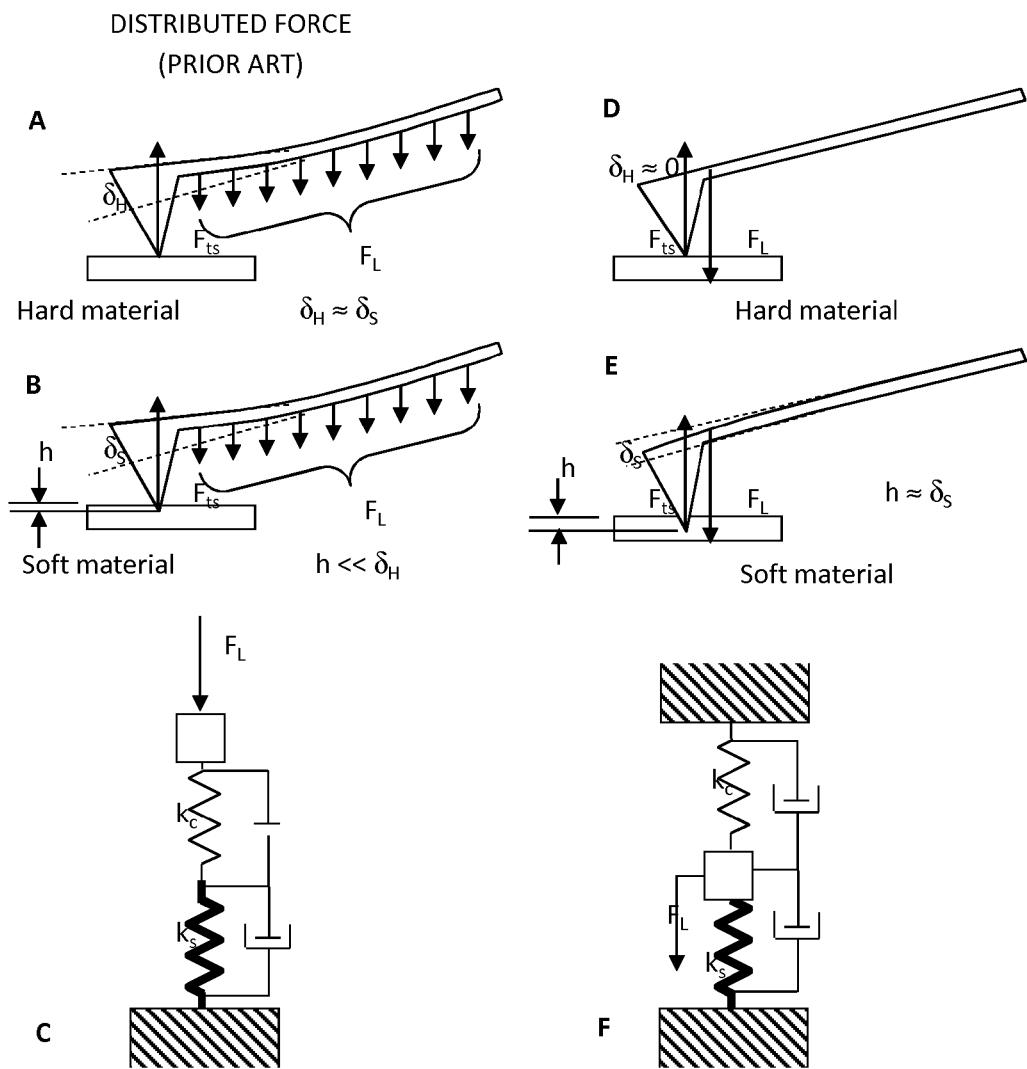
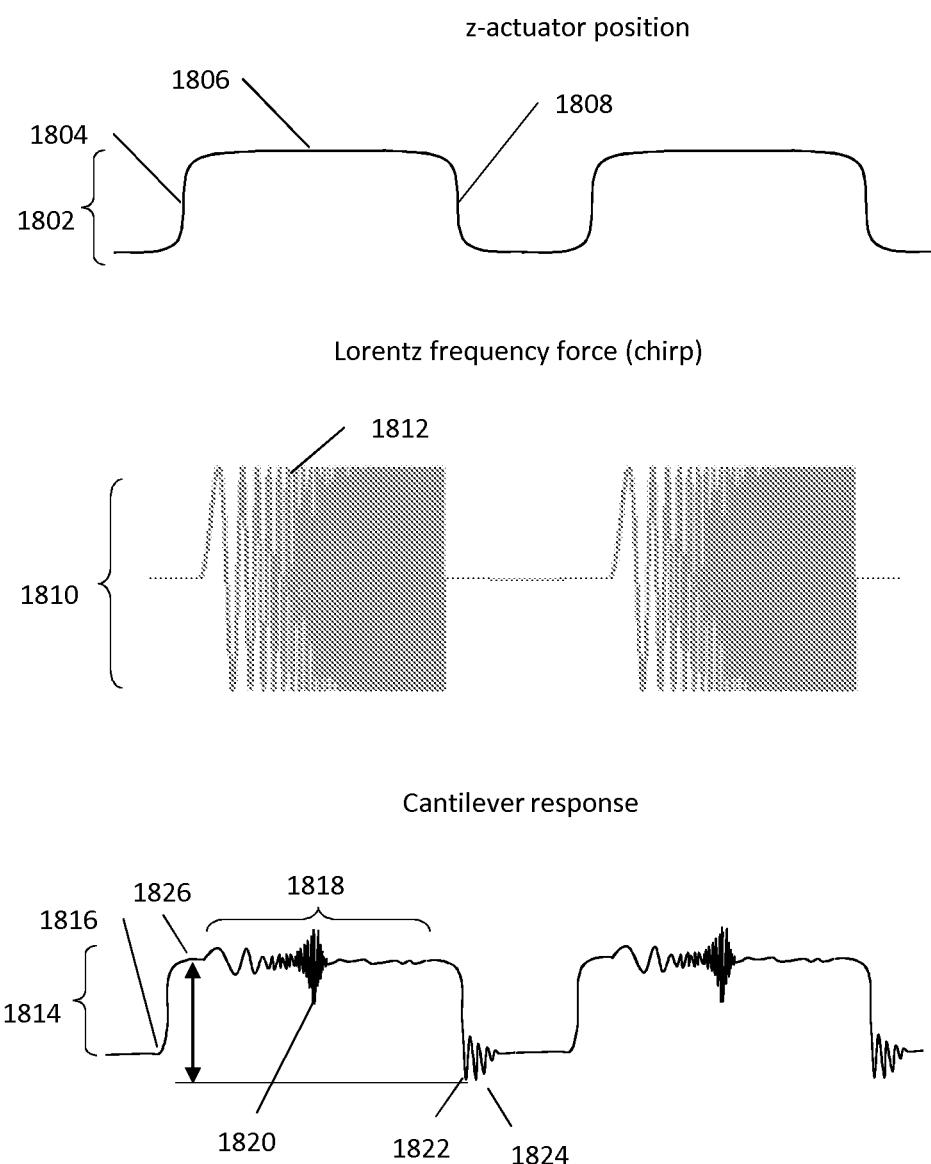
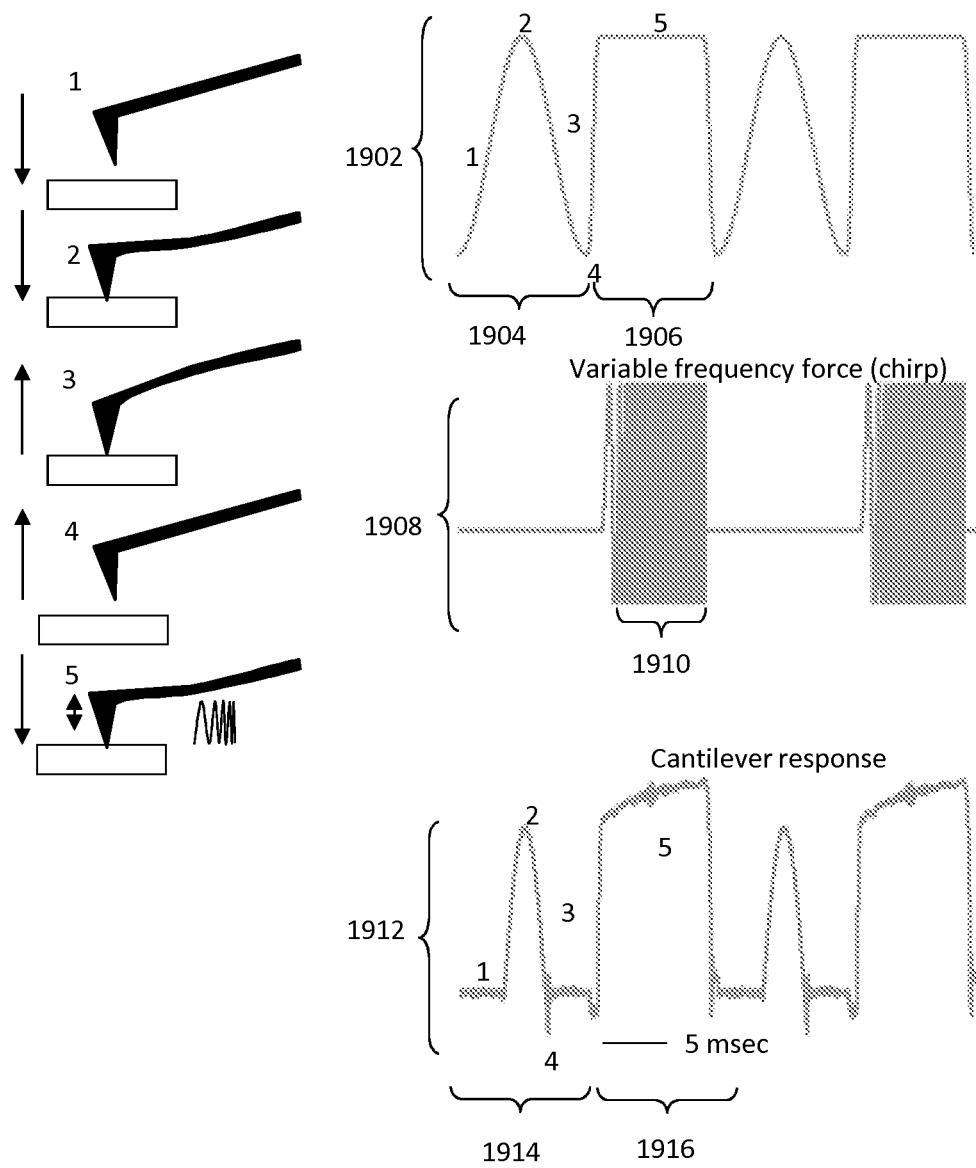
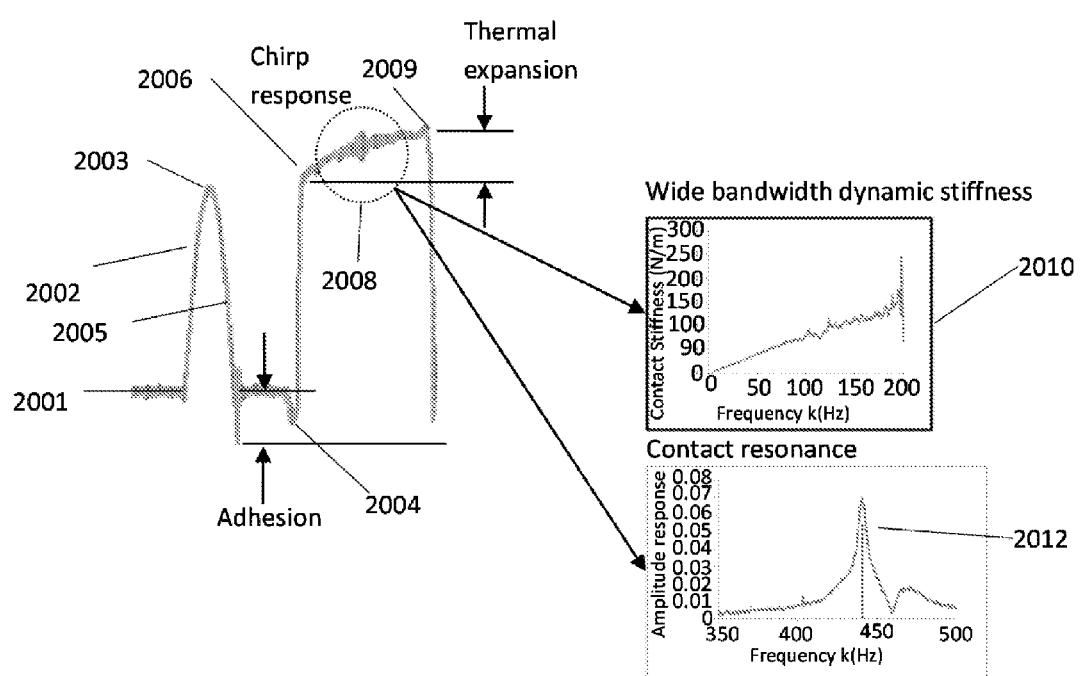
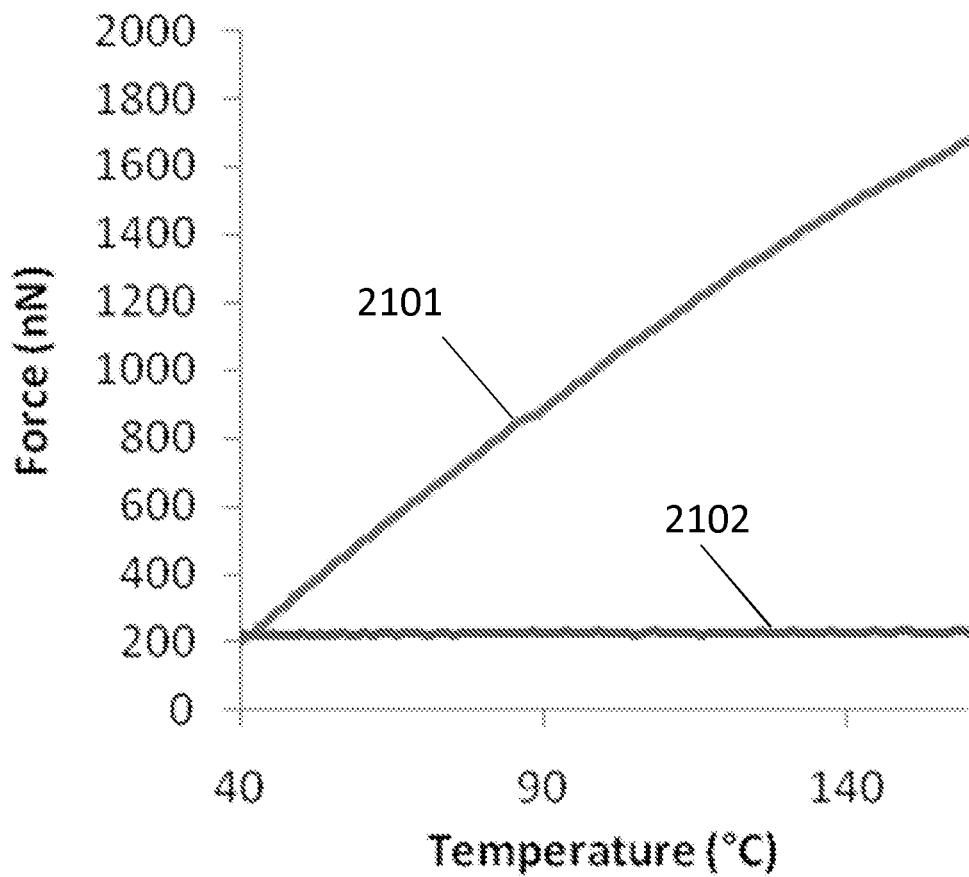


Figure 17

**Figure 18**

**Figure 19**

**Figure 20**

**Figure 21**

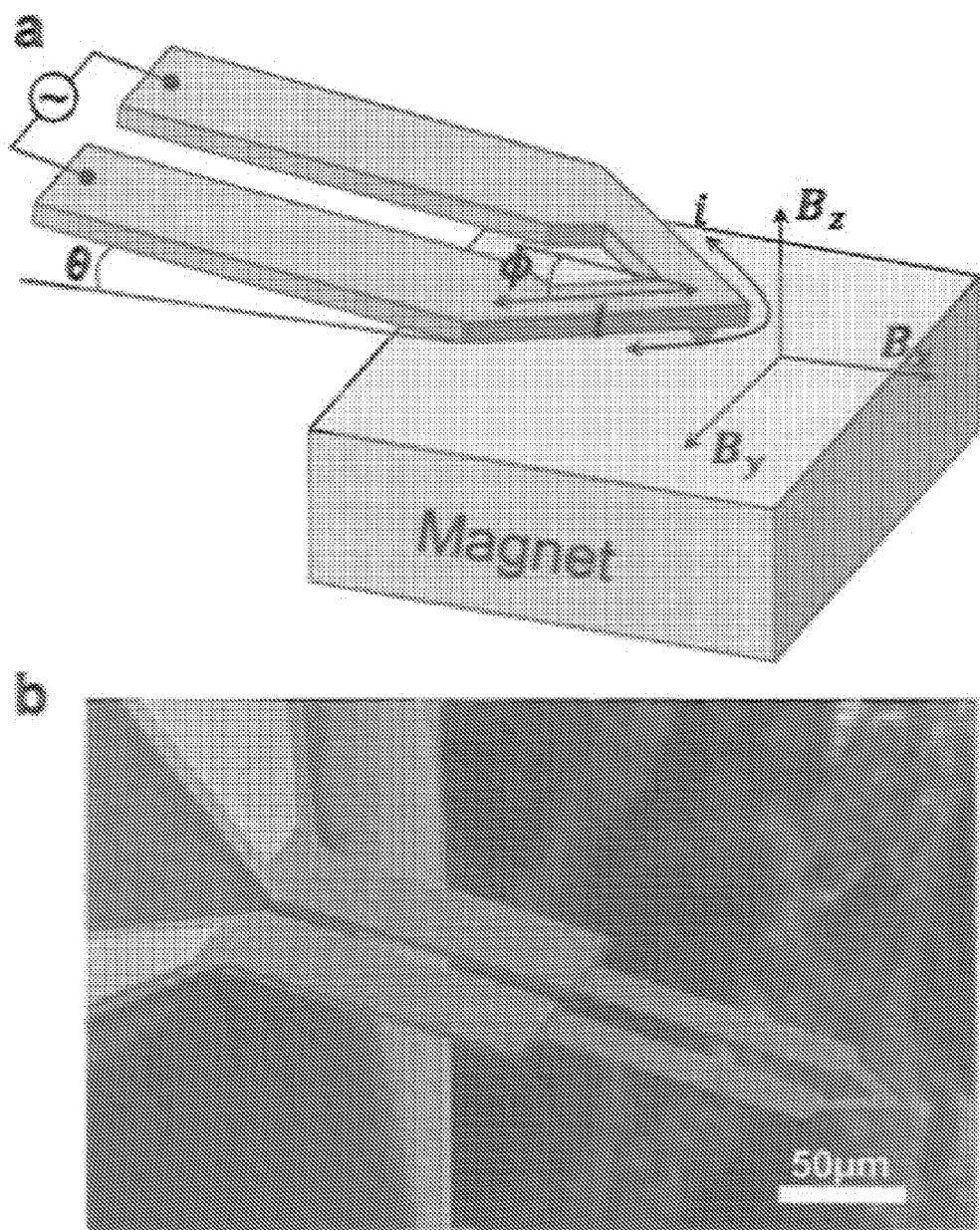
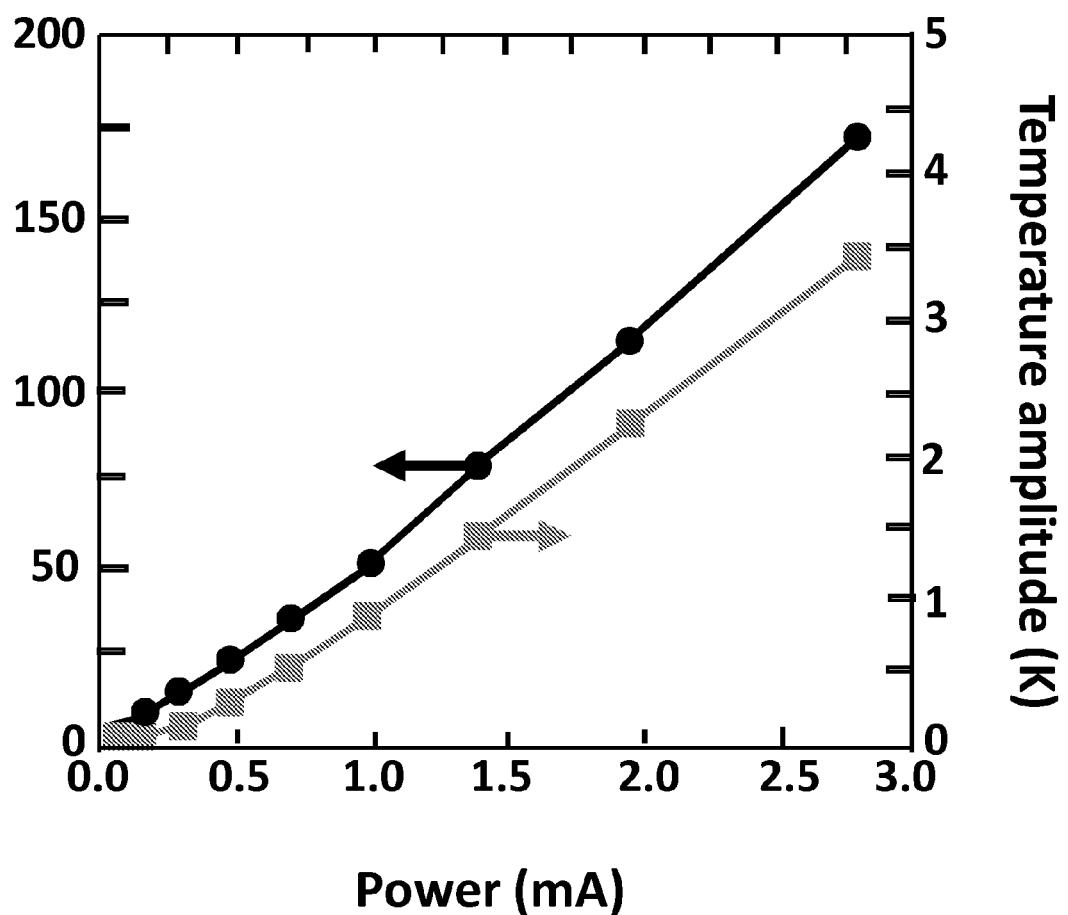
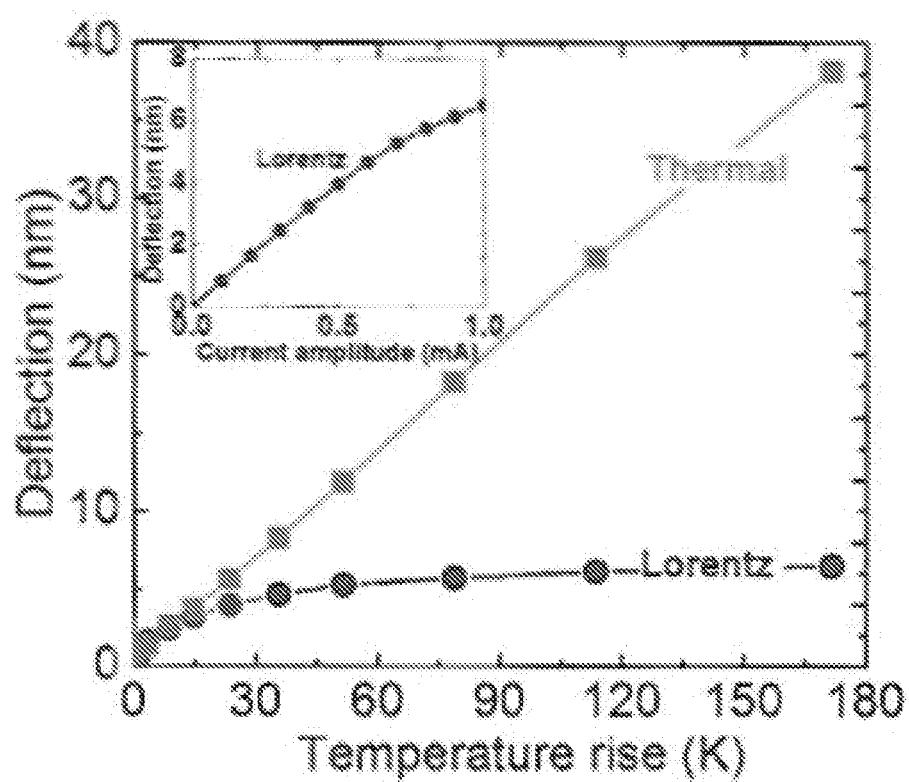


Figure 22

**Figure 23**

**Figure 24**

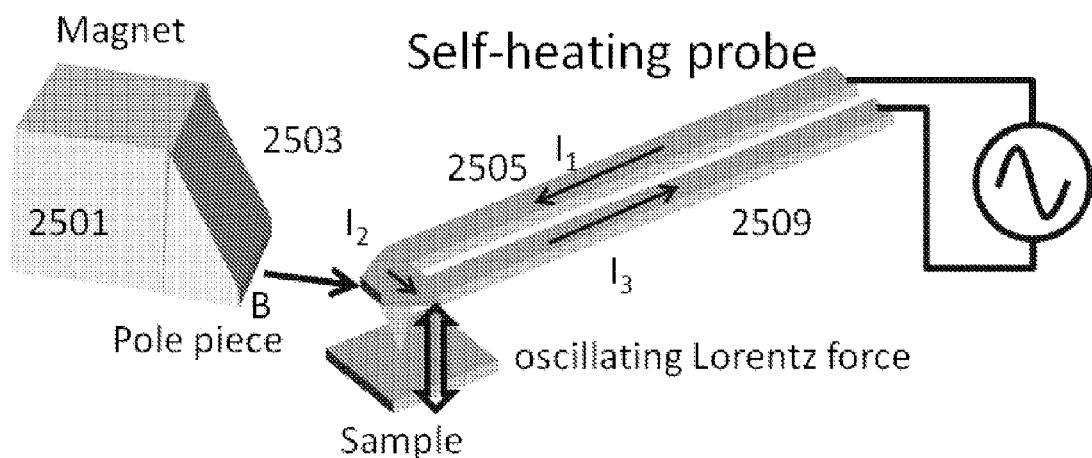


Figure 25A

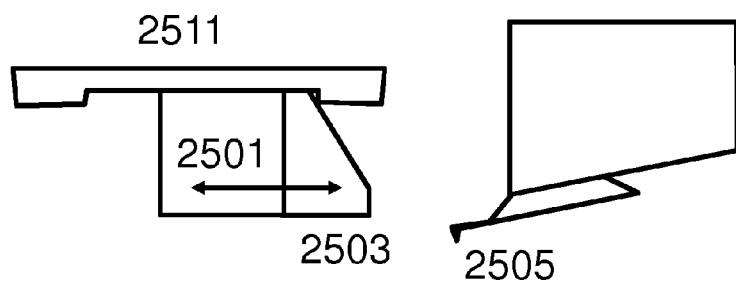


Figure 25B

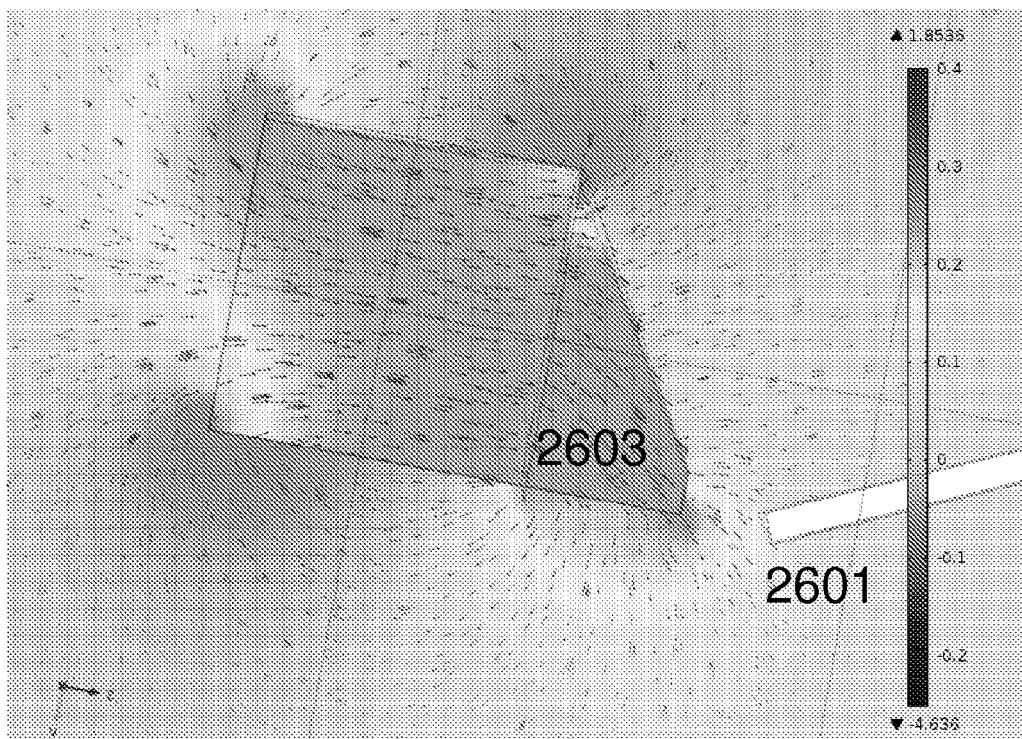


Figure 26

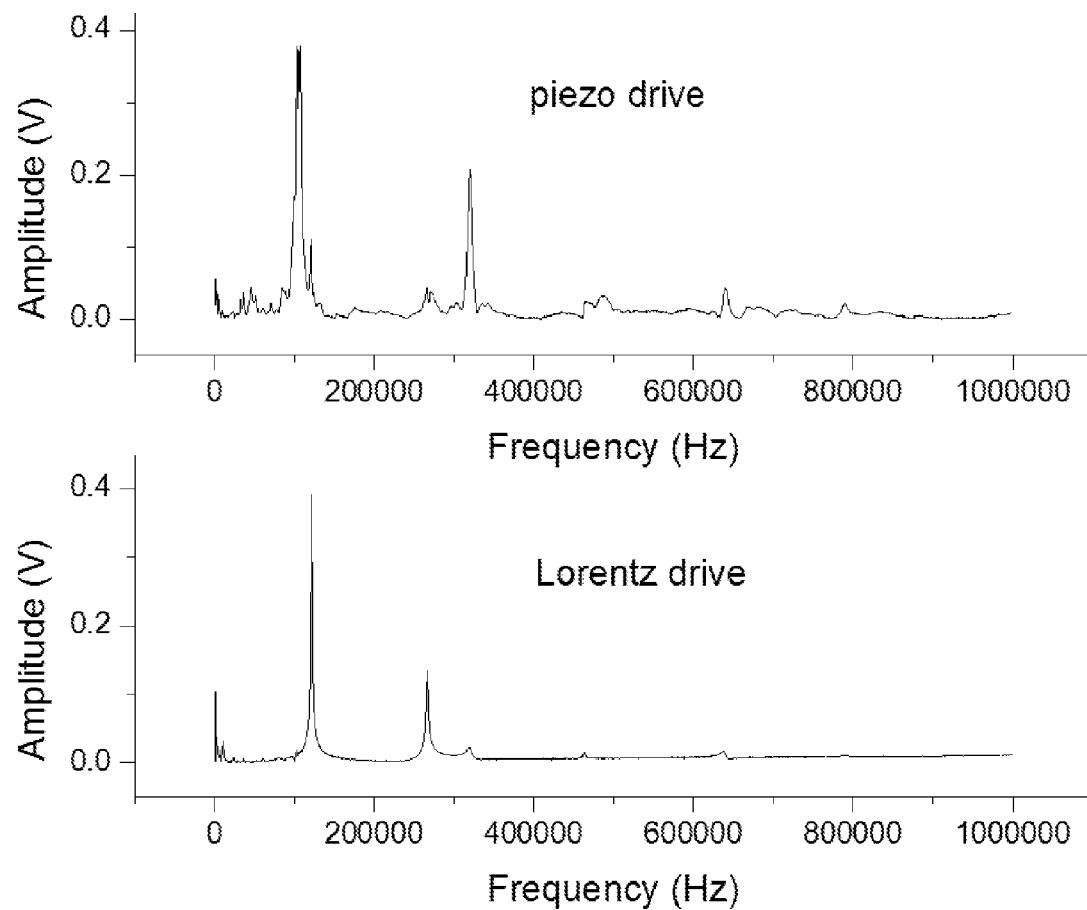


Figure 27

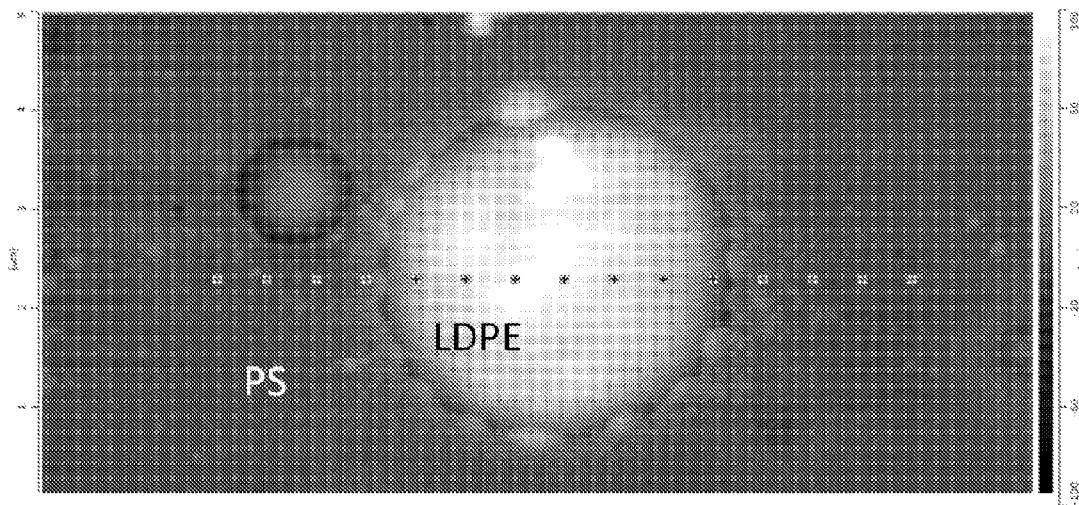


Figure 28A

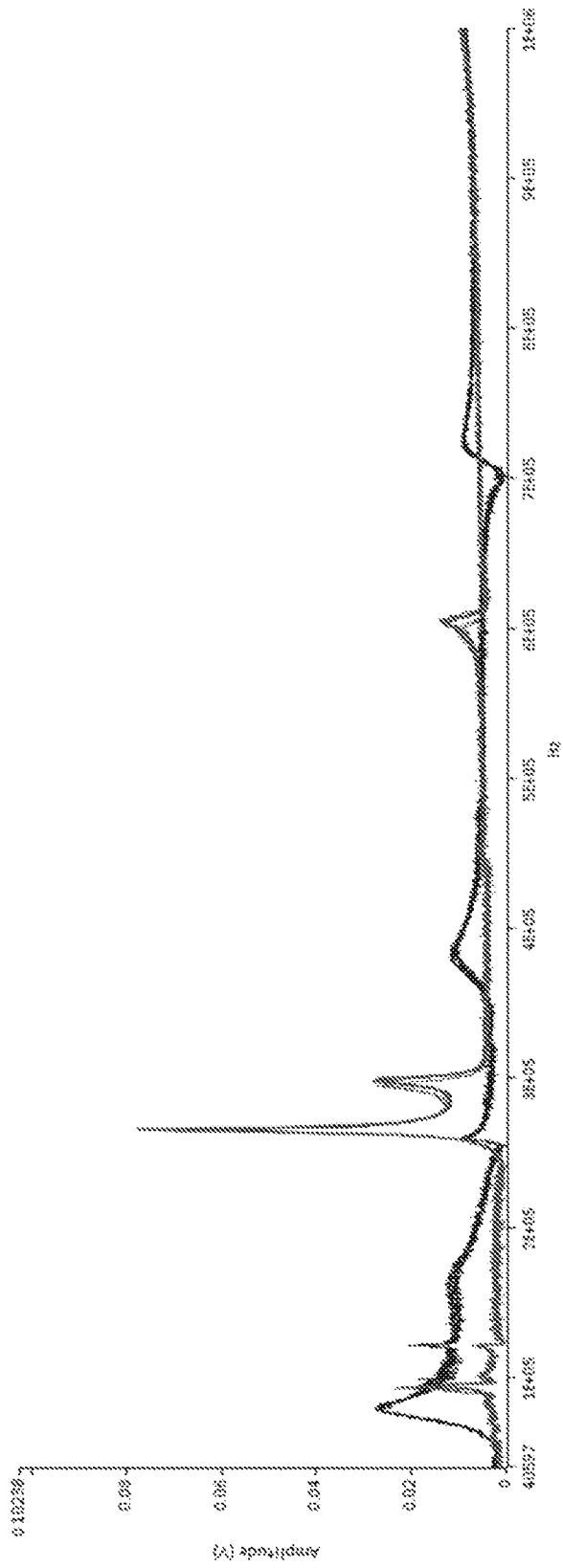


Figure 28B

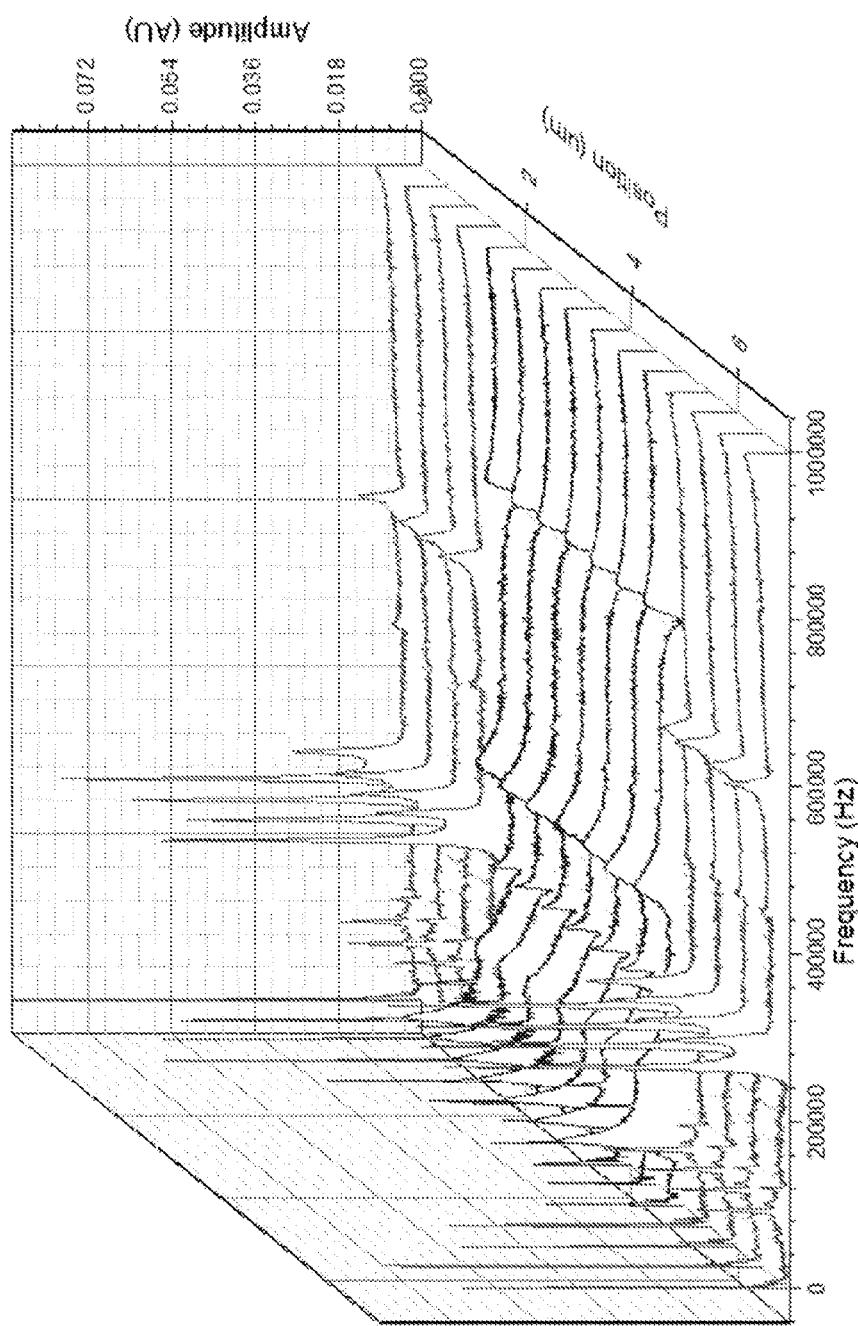


Figure 28C

AFM height

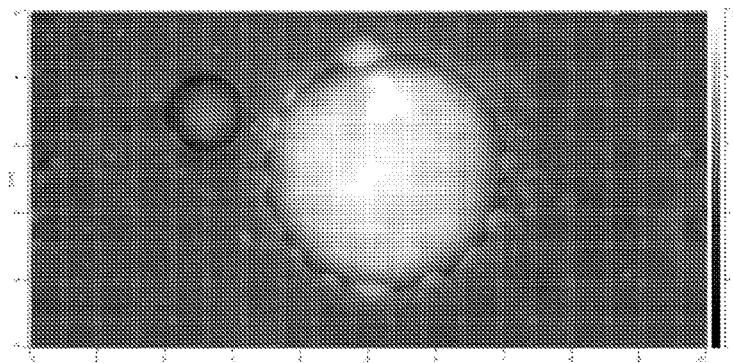


Figure 29A

Amplitude

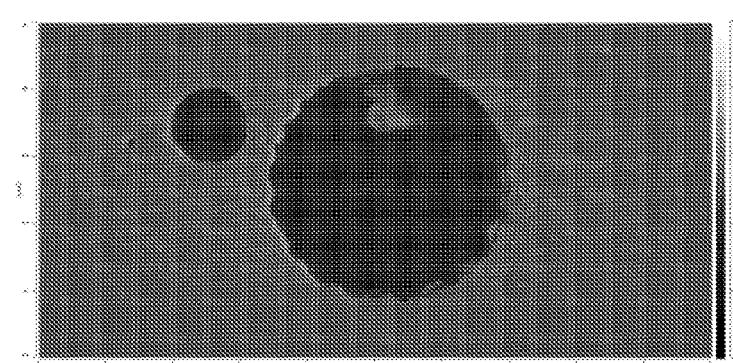


Figure 29B

Phase

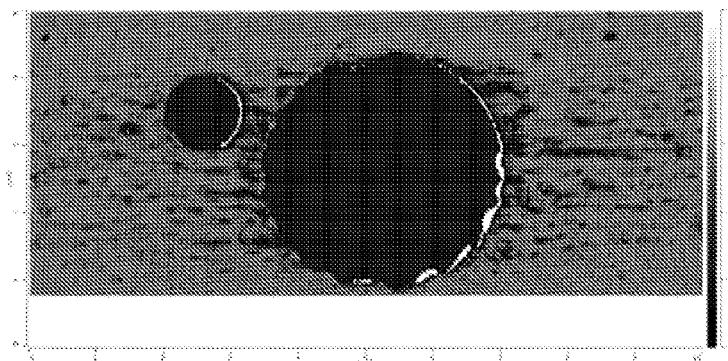


Figure 29C

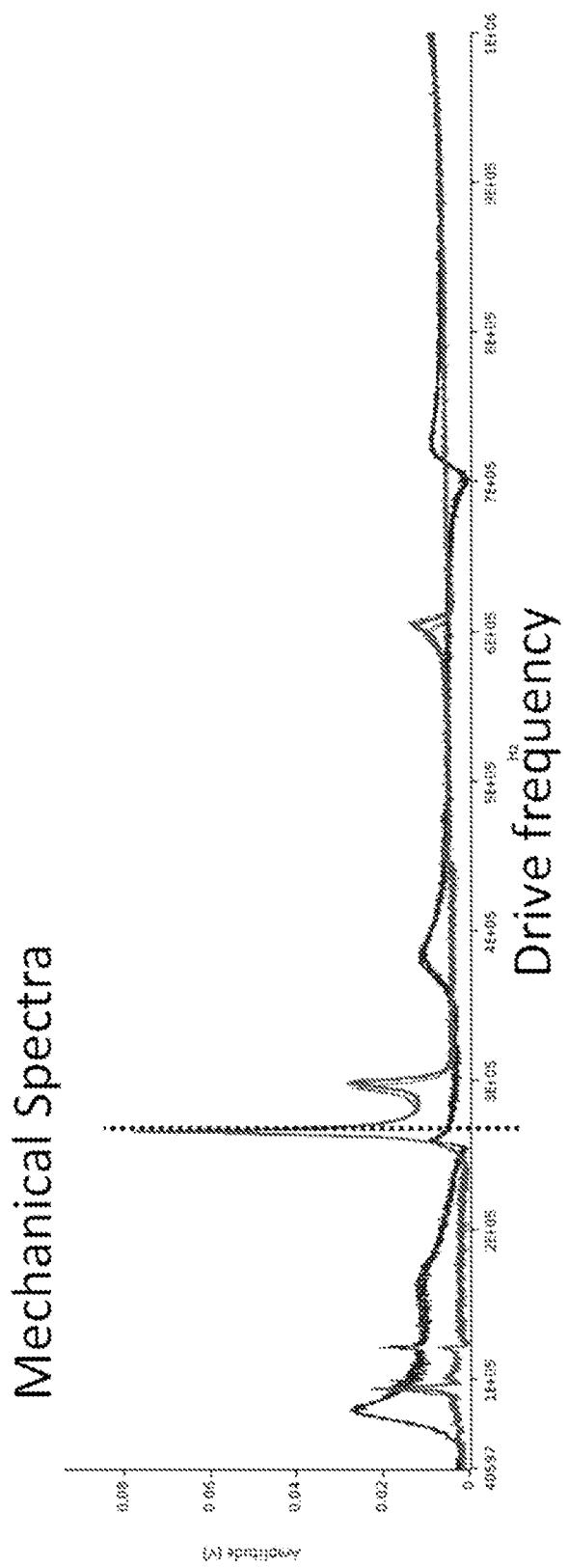


Figure 29D

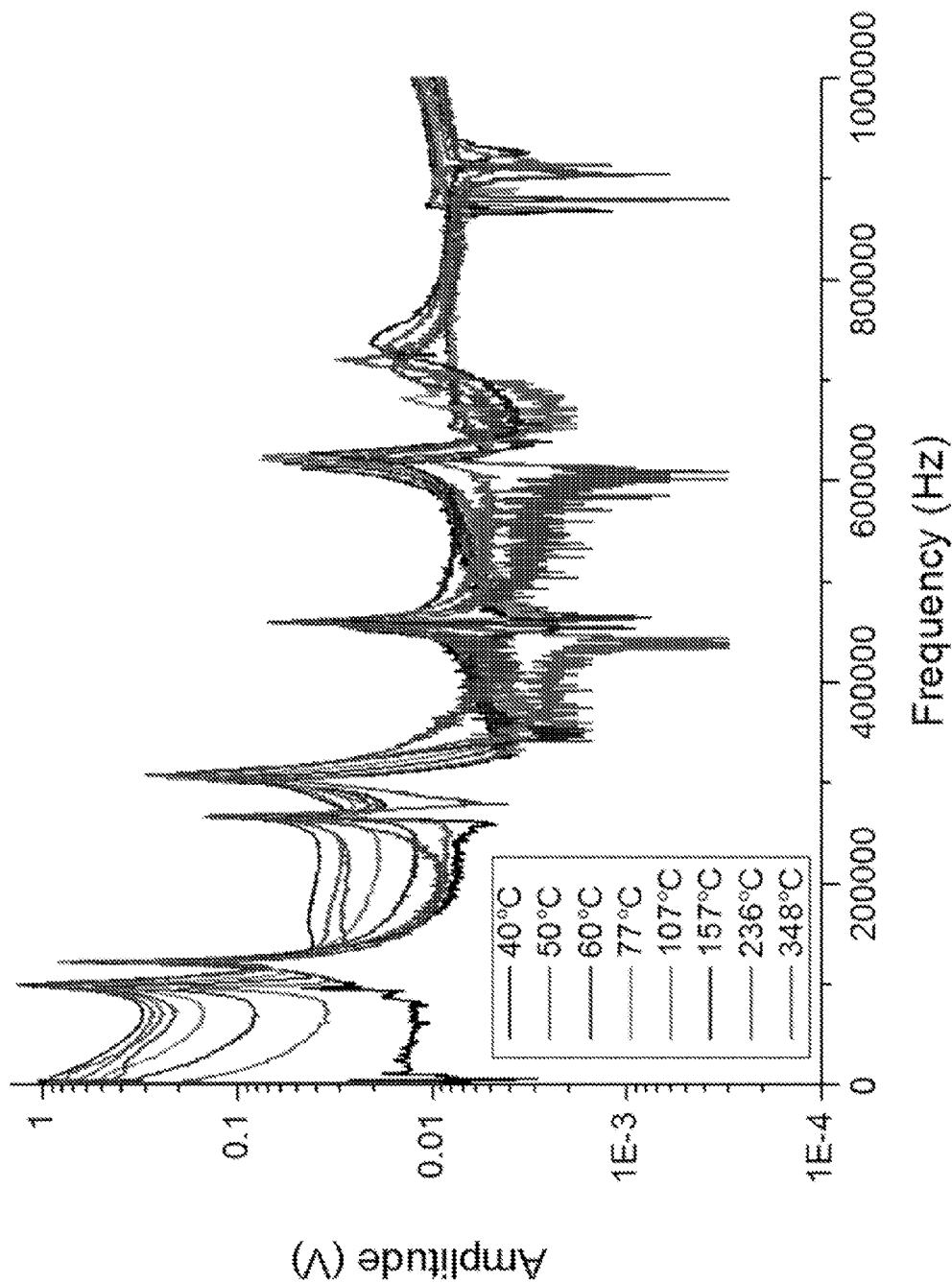
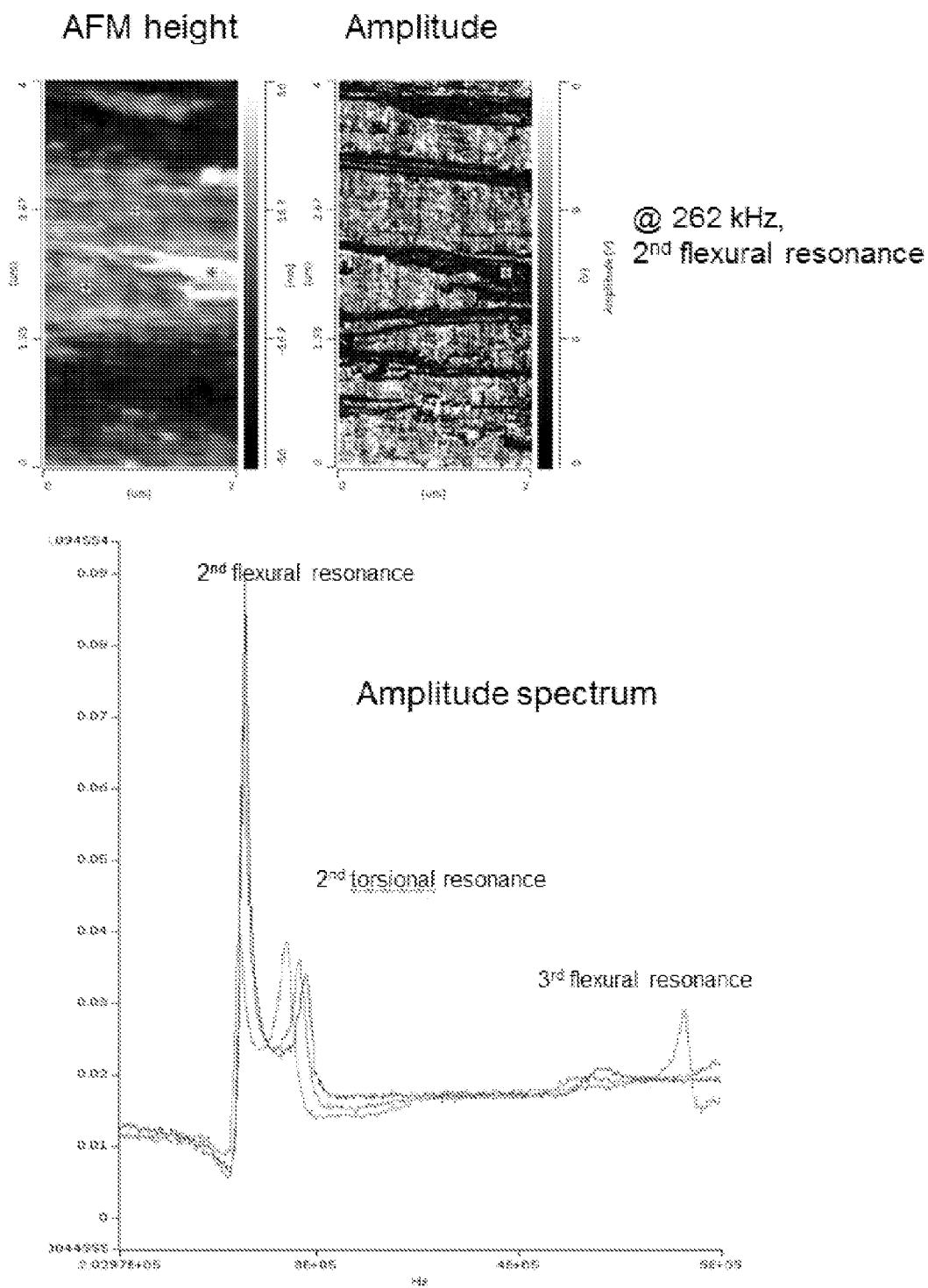


Figure 30

**Figure 31**

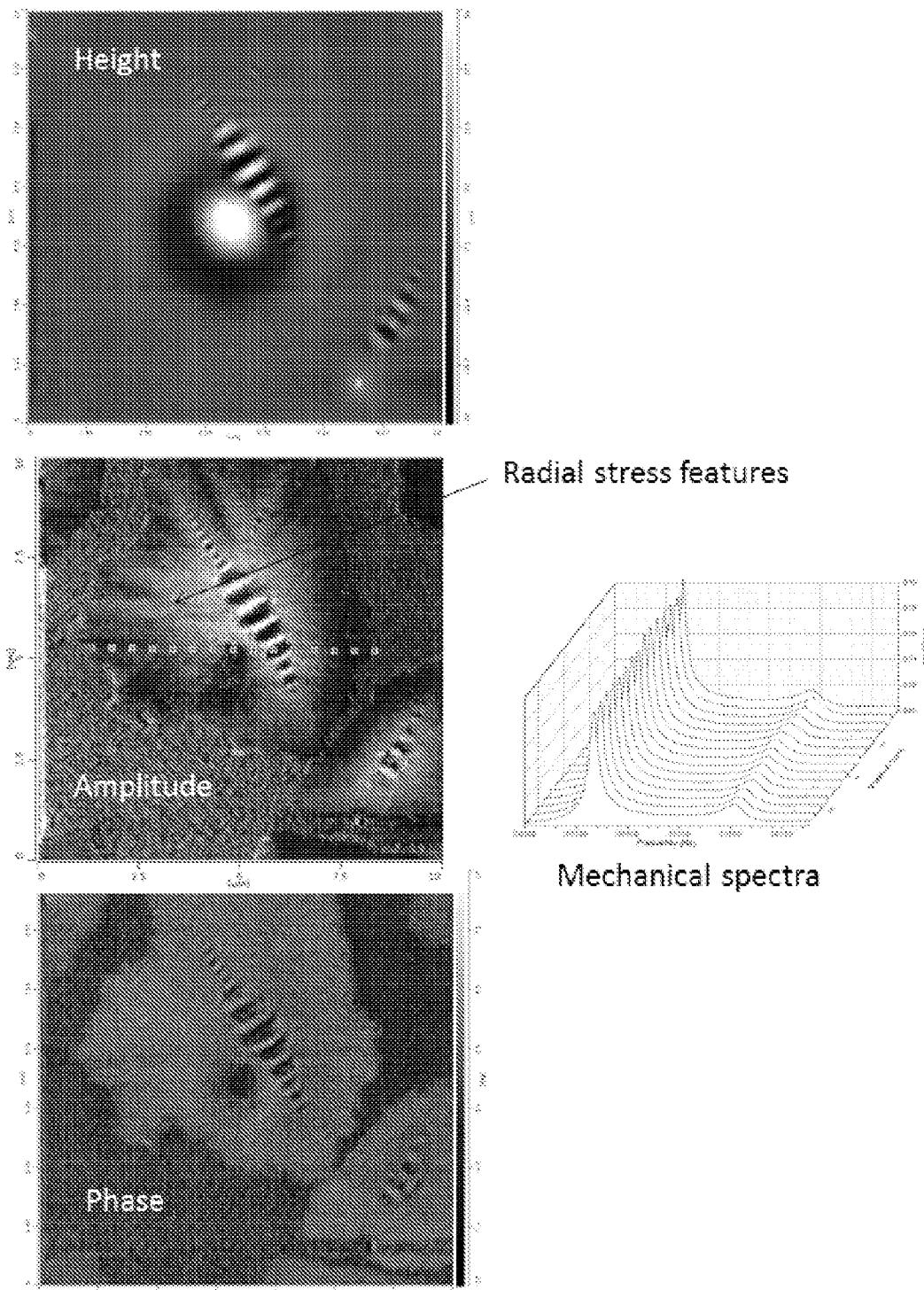
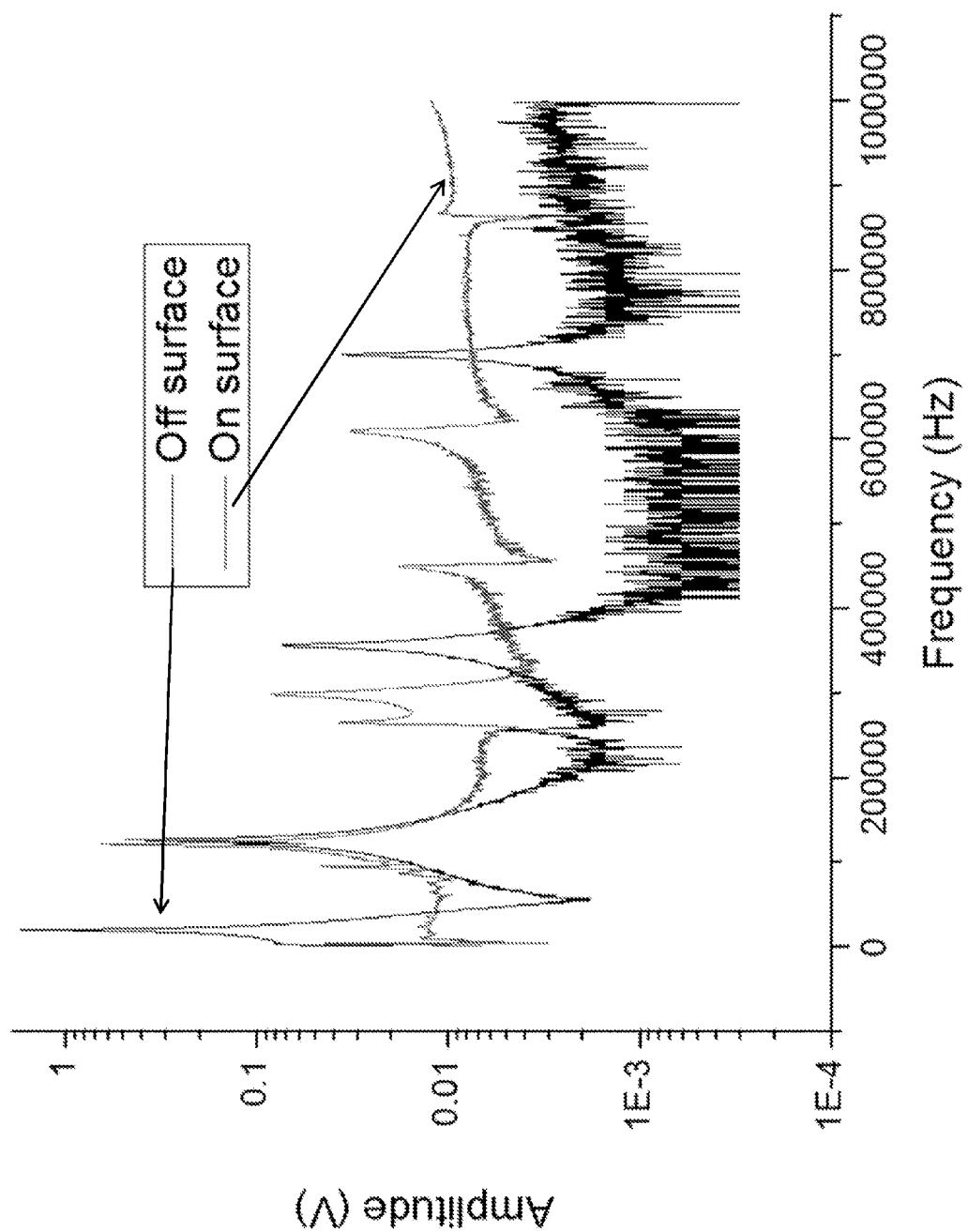
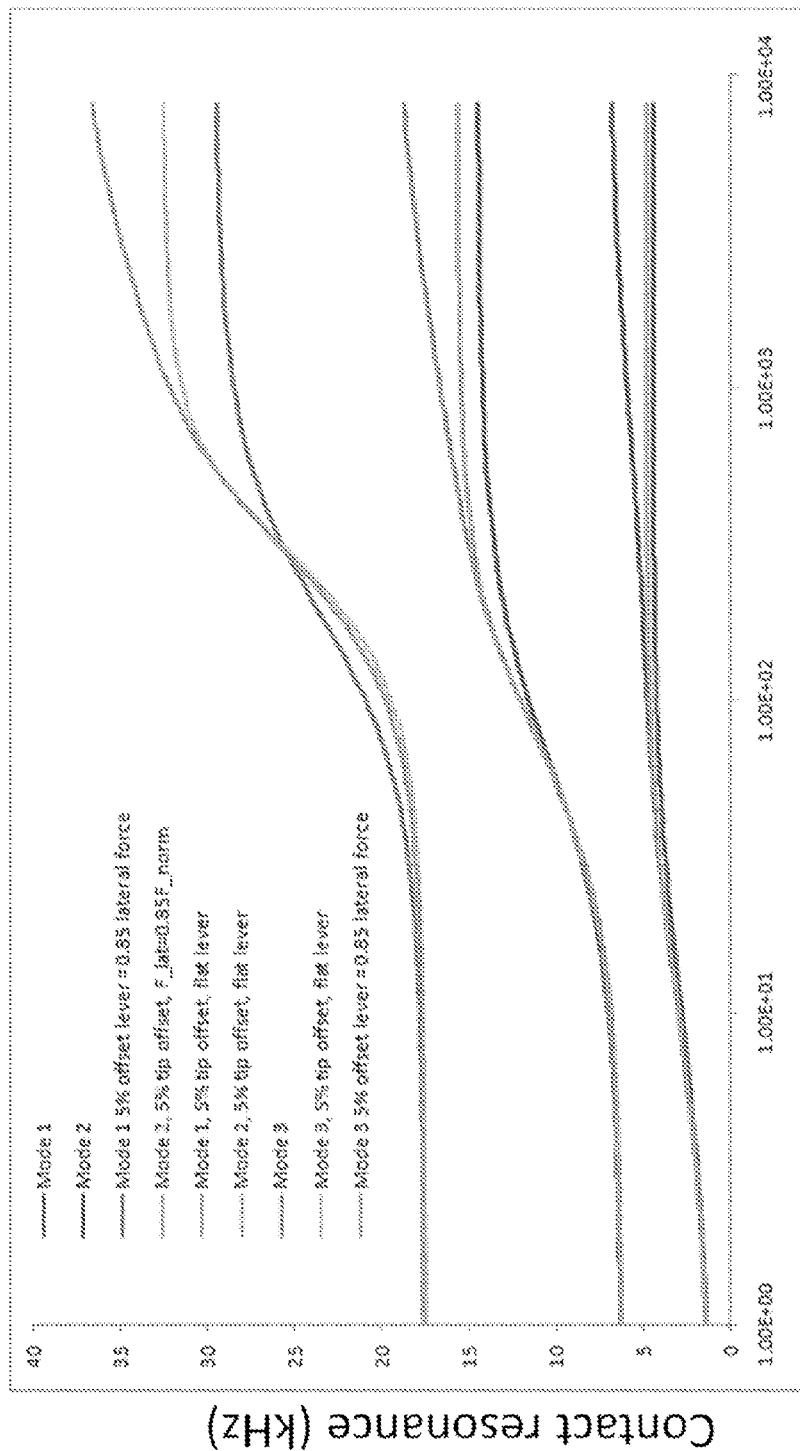


Figure 32

**Figure 33**



Relative stiffness ks/kc

Figure 34

1

**MAGNETIC ACTUATION AND THERMAL
CANTILEVERS FOR TEMPERATURE AND
FREQUENCY DEPENDENT ATOMIC FORCE
MICROSCOPY**

**CROSS-REFERENCE TO RELATED
APPLICATIONS**

This application is a continuation-in-part of U.S. Nonprovisional application Ser. No. 13/304,306, filed Nov. 23, 2011, which claims the benefit of and priority to U.S. Provisional Application 61/523,572, filed on Aug. 15, 2011, each of which are hereby incorporated by reference in their entireties. This application also claims the benefit of and priority to U.S. Provisional Application 61/660,195, filed on Jun. 15, 2012, which is hereby incorporated by reference in its entirety.

**STATEMENT REGARDING FEDERALLY
SPONSORED RESEARCH OR DEVELOPMENT**

This invention was made with governmental support under NSF-IIP-1047437 awarded by the National Science Foundation and FA9550-08-1-0407 awarded by the Air Force Office of Scientific Research. The government has certain rights in the invention.

BACKGROUND

The atomic force microscope (AFM) enables nanomechanical measurements with high spatial resolution. Some AFM imaging modes require the cantilever tip to oscillate in contact with or near the surface. The cantilever oscillation can be actuated with piezoelectric, electrostatic, photothermal, thermomechanical or magnetic schemes.

The first papers reporting magnetic actuation of a microcantilever used a magnetic coating or particle on cantilever and an external AC field. The presence of the magnetic material on the cantilever comes with challenges in fabrication and implementation. Buguin and co-workers proposed an improved Lorentz force actuation scheme, where the magnet was external to the cantilever as described in U.S. Pat. No. 6,862,923. In this scheme, the actuation was driven by an AC current flowing through a cantilever current loop in the presence of an external magnetic field. Buguin taught the use of a uniform magnetic field oriented substantially perpendicular to the current loop. A related approach by Enders and co-workers analyzed cantilever excitation spectra induced by Lorentz force and studied thermomechanical spectrum at high power. A Lorentz force actuation scheme is market commercially by Asylum Instruments for actuation of soft cantilevers in fluid, called the "iDriven™ Fluid Imaging Option."

Similarly, U.S. Patent Application Publication US 2011/0126329 discloses a magnetically actuated cantilever chip including a centrally supported cantilever having a magnetic element positioned on the cantilever body at an end opposite to the probe tip. Actuation of the cantilever is accomplished by flowing a current through a loop on the cantilever chip positioned nearby to the magnetic element to induce a local oscillation at the magnetic element. Here both the magnetic elements and current loops are constructed to generate extremely localized interactions to permit independent operation of arrays of cantilevers.

U.S. Pat. No. 6,668,627 discloses a magnetically excited cantilever. Here, the cantilever is placed in a magnetic field and a current is passed through a loop in/on the cantilever to induce vibrations. The cantilever devices include chemically sensitive films for use as highly sensitive chemical sensors.

2

The cantilever devices are non-heating and are designed to limit heat generation in the devices to minimize the impact of heat on and achieve non-interference with the chemically sensitive films.

- 5 Within the field of AFM, self-heating AFM cantilever probes have been developed. An example is shown in FIG. 1. Similar probes are described for example in U.S. Pat. No. 7,497,613, which is incorporated by reference. These cantilever probes 101 have conductive arms 103 and include a resistive heater 107 in the vicinity of the tip of the end 106 of the cantilever structure. When current is directed through the resistive heater, the dissipated power heats the cantilever and tip such that a microscopic region of a sample can be locally heated. The probe tips are very sharp, <20 nm end radius and thus can be used to measure thermomechanical properties of materials on the sub-micron and sub-100 nm length scales. With these probes it has been possible to investigate the nanometer-scale thermal properties of materials and perform nanometer-scale lithography.
- 10 Contact Resonance AFM. One measurement mode of AFM is called contact-resonance AFM (CR-AFM). This technique is described in various publications by Yamanaka, Rabe and Arnold, Yuya, Turner and Hurley, Stan and Cook for example, and patents including U.S. Pat. No. 6,983,644. In 15 this mode a cantilever is oscillated with its probe tip in contact with a sample surface. With this arrangement, the cantilever will resonate at frequencies that are dependent on the mechanical properties of both the cantilever and the sample. By measuring shifts in these frequencies, the mechanical properties of a sample can be inferred. A major challenge with CR-AFM has been the method of actuating the cantilever. Most researchers use piezoelectric actuators or ultrasound transducers to excite cantilever resonances. While these can work, they suffer from bandwidth and power limitations, and 20 parasitic resonances. The current inventors found that these parasitic resonances can be particularly problematic while performing measurements of sample mechanical properties as a function of temperature. The reason is that the mechanical properties of a polymeric material can change dramatically as a function of temperature. As such, during variable 25 temperature measurements, it is increasingly likely that a contact resonance frequency of the cantilever can sweep through a parasitic resonance, thus compromising the quality of the measurement.
- 25 Dynamic Mechanical Analysis. A very commonly used instrument for characterizing the bulk properties of a material is dynamic mechanical analysis (DMA). DMA works by applying an oscillating stress to a sample and measuring the time-dependent strain, or the strain rate. Analysis of DMA data gives information about material stiffness, viscosity, thermal transitions and energies, for example. DMA is a critical and widely used tool to measure the viscoelastic properties of bulk materials, but suffers from extremely slow 30 measurement speed and complete lack of spatially resolved information. Large and growing material classes employ nanoscale composite structures to achieve desired material properties. Conventional DMA cannot measure the local behavior within these heterogeneous materials, producing only information about the aggregate bulk behavior. There is 35 a growing need for instrumentation that can characterize micro and nano-structured materials on the length scales they are engineered.
- 35 Some attempts have been made to address this issue, including phase imaging, pulsed force microscopy, nanothermal analysis, and nanoDMA. Phase imaging (U.S. Pat. RE36, 488) involves measuring changes in the cantilever oscillation 40 phase while in tapping mode. These variations can illuminate 45

variations in damping, friction, adhesion and elasticity, but cannot easily distinguish or quantify between these effects. Nanothermal analysis (nanoTA) has been commercialized by Anasys Instruments. NanoTA records the cantilever deflection while ramping the tip temperature with self-heated cantilevers. NanoTA can identify glass transitions on some materials by observing changes in slope of the deflection versus temperature curve. It has been successful on many materials, but can fail on some samples, especially those that are highly crosslinked, highly crystalline, and/or very thin, e.g. <100 nm.

A commercial instrument called nanoDMA has been developed by the Hysitron company. It applies an oscillating force to a sample surface using a sharp tip. The maximum oscillation frequency reported by the manufacturer is 300 Hz, roughly similar to conventional dynamic mechanical analyzers (DMA). It also suffers from slow measurement speeds similar to conventional DMA, as discussed below.

The slow measurement speed of DMA and similar bulk measurements results in large part from the macroscopic scale of the heated region of the sample and attendant instrumentation. The sample, and often a significant portion of the DMA apparatus, is typically enclosed in a large temperature controlled enclosure. Because of the large volume that must be heated and cooled, it is not uncommon to employ heating/cooling rates in the range of 1-10° C. per minute. It is also not uncommon to wait for 30 minutes or more for the system to stabilize at each temperature. Thus, to characterize the viscoelastic properties of a sample at a significant plurality of frequencies and temperatures can take hours to days.

Modern materials are also subject to stresses and strains over an extremely wide range of frequencies from static loads up to high vibrations encountered in automotive and aerospace applications, to extreme shocks encountered in impact and ballistic applications. No current tool can rapidly examine the temperature dependent viscoelastic response of these materials on the length scales they are being engineered. Further, no current tool can examine material properties on this length scale and over the wide range of strain rates encountered by modern materials.

SUMMARY

Embodiments of the invention involve the direct force actuation of the tip of self-heatable cantilever for the characterization and manipulation of material at the sub-micron and nanometer scale over a wide range of time scales, frequencies, and temperatures. Using a self-heating cantilever in combination with Lorentz force actuation, embodiments have achieved material characterization with a frequency range, temperature range, and measurement speed previously unavailable in the prior art. Specifically, the inventors have achieved a strain frequency ~1000x higher than conventional DMA and a measurement throughput around ~1000x higher than conventional DMA or conventional variable temperature AFM. These improvements are achieved, for example, due to the high force bandwidth and large available force of the Lorentz force actuation, the high heating rates of the self-heatable cantilevers, and the microscopic regions of the sample that are heated.

Referring to FIG. 1, a self-heating cantilever embodiment comprising two conducting cantilever arms and an end region with a heater and a tip is interacted with a magnetic field from a magnetic field source. In embodiments, the magnetic source is a permanent magnet and/or an electromagnet. When current flows through the arms and heater region of the cantilever, a Lorentz force can act on the cantilever. Selection of an

appropriate direction for the magnetic field can result in a large force on the cantilever, on the scale of many nanonewtons (nN) up to several microneutons (μ N). This force is sufficient for many purposes and embodiments including 5 direct force actuation of the probe tip into the sample, force modulation, intermittent contact, active force control, and forced-based lithography, for example. In an embodiment where the two arms of the cantilever are parallel, the magnetic interactions can be arranged such that the net force on the 10 parallel cantilever arms is zero or nearly zero, resulting in a magnetic force primarily at the tip end of the cantilever. This can provide substantial benefit, for example, for application of force to the sample, since the force is applied very close to the tip, with minimal intervening mechanical structure that 15 can attenuate the force. This is in contrast to many techniques for oscillating AFM cantilevers where the force is applied at the base of the cantilever (most piezoelectric actuation schemes). It is also in contrast to other capacitive and magnetic techniques that apply a force over an extended area of 20 the cantilever. In embodiments when the force is applied close to the tip, rather than along some portion of the cantilever body, more direct control of the tip-sample interaction can be maintained. The prior art arrangement that applies force at the 25 base or along the body or some portion of the body can limit both the magnitude and frequency of forces that can be applied to the tip. For example, forces applied at the base or body of the cantilever at frequencies above the first resonant frequency of the cantilever are dramatically attenuated by the transfer function of the cantilever. Applying the force near the 30 free end, for example, can also allow the cantilever to operate more efficiently compared to force application at some other location, due to the torque or moment on the cantilever that is maximized when a force is applied at the free end rather than at some position farther from the free end.

Another benefit of embodiments of the current invention is 35 the ability to rapidly measure a material response as a function of both temperature and frequency. Embodiments of the current invention have dramatic benefits over the prior art as they can explore the frequency and temperature dependence 40 of a material response from room temperature or below to 500° C. and up to 3 MHz in less than 1 minute and as short as a few seconds. In conventional DMA, measurements at such frequencies are impossible for measurements over this broad 45 a temperature range. Embodiments of the current invention can achieve this performance, for example, because the self-heatable AFM probes only heat a microscopically small region of the sample, compared to the entire sample and significant part of the apparatus for variable temperature AFM and DMA. Because of the microscopic heating area, the 50 sample temperature can stabilize in milliseconds or less, thus supporting extremely fast temperature ramp rates. The inventors have demonstrated temperature ramp rates as high as 600,000° C. per minute, compared to 1-10° C./minute commonly used in variable temperature DMA and AFM. Even 55 much more modest heating rates of 600° C./minute achieve dramatic benefits over the prior art.

Embodiments of the current invention also benefit from a 60 very high strain frequency range. The Lorentz mechanism can optionally apply forces at arbitrarily high frequencies. The practical limit for certain embodiments is set by the maximum frequency that the AC current can be driven through the cantilever, as limited by the resistance, inductance, and capacitance of the self-heatable probe and associated wiring. Without special preparation, in embodiments the inventors 65 have delivered current to the probe and hence Lorentz forces to the tip up to 3 MHz. Higher bandwidths can be achieved using shielding techniques used, for example, in scanning

microwave microscopy or scanning impedance microscopy, which can operate up to GHz frequencies. These can include planar or coaxial waveguides integrated into the cantilever probe and/or specialized shielding techniques used to minimize stray capacitance and optimize the impedance matching between the source and load. For example, scanning impedance microscopy has been performed at frequencies up to 100 GHz, as described by Tanbackuchi et al in *Scanning Impedance Probe Microscope*, Nanotechnology, 2008. NANO '08. 8th IEEE Conference on, 18-21 Aug. 2008, 2008; 2008; pp 218-219. Higher bandwidths could also be achieved by using a microcantilever that has been engineered with different electronic properties, for example resistance, inductance, or capacitance. These electronic properties could be modified without modifying the thermal or mechanical properties of such heated cantilever probes. Such techniques are known to those skilled in the art.

In a specific aspect, provided are methods of operating a probe microscope. Methods provided herein are useful, for example, for characterizing a region of a sample with sub-micron spatial resolution. A specific method of this aspect comprises the steps of: interacting a probe tip of a self-heating cantilever probe with a surface of the sample; providing a magnetic source that generates a magnetic field in proximity to the cantilever probe; and passing a current through the self-heating cantilever probe so as to generate a force on the cantilever probe due to an interaction between the current and the magnetic field. Optionally, the method further comprises a step of measuring a signal indicative of the motion of the cantilever probe. In a specific embodiment, the magnetic field is substantially aligned along the length of the cantilever probe. In a specific embodiment, the cantilever probe comprises two substantially parallel arms such that a Lorentz force on each of the two arms substantially cancels and a primary net force is generated at a tip end of the cantilever probe.

Optionally, for methods of this aspect, the current is an alternating current, for example comprising an alternating current at one or more frequencies. In such embodiments, an oscillatory force is optionally generated on the cantilever. Optionally, the current passing step is repeated at a plurality of frequencies and the method further comprises a step of measuring a frequency dependent response of the cantilever probe interacting with the sample surface. In one embodiment, a frequency of the oscillatory force is greater than 10 kHz. In one embodiment, a frequency of the oscillatory force is greater than 100 kHz. In one embodiment, a frequency of the oscillatory force is greater than 1 GHz. In one embodiment, a frequency of the oscillatory force is greater than 10 GHz. Optionally, methods of this aspect further comprise a step of determining a contact resonant frequency of the cantilever probe. Optionally, methods of this aspect further comprise a step of measuring a viscoelastic response of the sample.

In embodiments, a number of techniques are useful for measuring the temperature of a cantilever and/or the cantilever probe tip. In one embodiment, the cantilever resistance and/or I-V characteristics are used to measure the cantilever temperature, as described, for example, in the following references, hereby incorporated by reference to the extent not inconsistent herewith: Lee, J., T. L. Wright, T. Beecham, B. A. Nelson, S. Graham, W. P. King, "Electrical, Thermal, and Mechanical Characterization of Silicon Microcantilever Heaters," Journal of Microelectromechanical Systems, 15, 1644-1655, 2006. Nelson, B. A., and W. P. King, "Temperature Calibration of Heated Silicon Atomic Force Microscope Cantilevers," Sensors and Actuators A, 140, 51-59, 2007. In

embodiments, cantilever frequency characteristics are used for measuring the cantilever temperature, as described, for example, in the following reference, hereby incorporated by reference to the extent not inconsistent herewith: Lee, J., T. L. Wright, T. Beecham, B. A. Nelson, S. Graham, W. P. King, "Electrical, Thermal, and Mechanical Characterization of Silicon Microcantilever Heaters," Journal of Microelectromechanical Systems, 15, 1644-1655, 2006. In embodiments, the cantilever bending or mechanical strain is used to measure the cantilever temperature, as described, for example, in the following reference, hereby incorporated by reference to the extent not inconsistent herewith: J. Zhao, R. Berger, and J. S. Gutmann, "Thermal contributions to the bending of bimaterial cantilever sensors," Applied Physics Letters 89, 033110, 2006. The temperature of the cantilever probe tip can also be separately calibrated, for example, by interacting the probe tip with a material of known melting temperature. The cantilever can be heated until the melting is detected by the cantilever probe. Calibration curves can be created that correlate the inferred tip temperature at melt versus the applied heater voltage, current, power and/or other similar control parameters. The probe tip temperature can then be estimated on an unknown sample by applying the calibration curve for the voltage, current, or power etc. used for a given measurement. For example, one of the assignees, Anasys Instruments, employs calibration samples of polyethylene terephthalate (PET), polycaprolactone (PCL), and high density polyethylene (HDPE) as melt calibration standards.

In certain embodiments, the cantilever probe comprises a heater region, for example having an electrical resistivity selected over the range of $1 \times 10^{-5} \Omega\text{-cm}$ to $15 \Omega\text{-cm}$. In one embodiment, a heater region comprises a thermistor. Thermistors are useful for simultaneously or alternately heating and measuring a temperature, for example by measuring a resistance of the thermistor. U.S. Pat. No. 7,928,343 and U.S. Patent Application Publication US 2011/0078834, hereby incorporated by reference, describes cantilevers and methods of making cantilevers including cantilevers comprising heater-thermometers as well as details regarding calibration of temperature versus measured heater-thermometer resistance.

Optionally, methods of this aspect further comprise a step of using the cantilever probe to change a temperature of a region of a sample and repeating the current passing step at a plurality of temperatures. Optionally, methods of this aspect further comprise a step of controlling a temperature of the cantilever probe. In specific embodiments, the temperature of the cantilever probe is ramped at a rate of more than $100^\circ \text{C./minute}$. In a specific embodiment, the step of controlling a temperature of the cantilever probe comprises heating the cantilever probe to a temperature selected over the range of 25°C. to 1000°C. , for example when in an air environment at room temperature. Higher or lower selected temperatures are also possible when the cantilever is in an environment other than air, such as gaseous environments, vacuum or reduced pressure environments, or liquid environments, such as water or buffer solution environments. Higher or lower selected temperatures are also possible when the cantilever is in an environment that is at a temperature other than room temperature.

In one embodiment, the step of controlling a temperature of the cantilever probe comprises heating the cantilever probe by a temperature of more than 1°C. , by a temperature of more than 3°C. , by a temperature of more than 5°C. , by a temperature of more than 10°C. , by a temperature of more than 25°C. , by a temperature of more than 50°C. , by a temperature of more than 75°C. or by a temperature of more than 100°C.

In another embodiment, the step of controlling a temperature of the cantilever probe comprises maintaining the temperature of the cantilever probe at a constant or a substantially constant value. In certain contexts, maintaining the temperature of the cantilever probe at a substantially constant value comprises maintaining the temperature of the cantilever probe within 1° C. of a selected temperature over a period of 1 μs or more, over a period of 10 μs or more, over a period of 100 μs or more, over a period of 1 ms or more, over a period of 10 ms or more, over a period of 100 ms or more or over a period of 1 s or more. For example, in one embodiment, the step of maintaining a temperature of a cantilever probe at a substantially constant value comprises providing a voltage or current to a self-heating cantilever probe to heat the cantilever probe to the constant temperature value and controlling the magnitude of the voltage or current to a level sufficient to maintain the temperature of the cantilever probe at the constant temperature value. Optionally, the temperature of the cantilever probe can be monitored, for example continuously or periodically, to provide an indication that an increased or reduced current or voltage is necessary for maintaining the temperature of the cantilever probe at the constant temperature value. In one embodiment, the temperature of the cantilever probe is monitored by measuring a resistance across a heating element of the cantilever probe. Optionally, a cantilever probe is provided in electrical communication with a temperature measurement system, for example a system that produces a signal indicative of a tip-sample temperature. Useful signals for measuring a cantilever temperature in this manner include, but are not limited to, cantilever resistance, cantilever I-V characteristics, cantilever frequency, cantilever frequency characteristics, cantilever bending characteristics and cantilever mechanical strain.

In an embodiment, a method of this aspect further comprises the step of determining a thermal transition temperature of the region of the sample by detecting a change in oscillatory motion of the cantilever probe as a function of temperature in response to an AC current passed through the cantilever probe. In a specific embodiment, the thermal transition is a glass transition.

Useful samples include those comprising a thin film having a thickness of less than 100 nm. Useful samples include those comprising a filled polymer having a fill percentage of greater than 10% by volume. Useful samples include those comprising a polymer having a crystallinity percentage greater than 10% by volume. Useful samples include those comprising a polymer having a crosslink percentage greater than 10% by volume.

In certain embodiments, the step of determining a contact resonant frequency is repeated at a plurality of cantilever probe temperatures. Useful embodiments include those further comprising the step of determining a thermal transition temperature of a region of the sample surface by detecting a change in the contact resonance frequency of the cantilever probe as a function of temperature.

One method embodiment of this aspect further comprises the step of calculating a signal indicative of a viscoelastic property of a region of the sample at a plurality of temperatures. Useful viscoelastic properties include those comprising a property selected from the group consisting of: E', E'', tan(delta) and any combination of these. Optionally, a method of this aspect further comprises the step of applying time temperature superposition to generate a master curve of the viscoelastic property of the region of the sample. Optionally, a method of this aspect further comprises a step of using time-temperature superposition factors to calculate an energy of the region of the sample.

Optionally, certain methods of this aspect further comprise the step of repeating the passing step at a plurality of regions of the sample to create a spatially resolved map of a property of the sample. Optionally, the property of the sample is selected from the group consisting of: topography, elasticity, damping, storage modulus, loss modulus, tan(delta), glass transition temperature, melting temperature and any combination of these.

Optionally, certain methods of this aspect further comprise 10 the step of adjusting a frequency of AC current passed through the cantilever probe such that the frequency substantially corresponds to a resonance frequency of the cantilever probe. For example, in one embodiment, the resonance frequency corresponds to a contact resonant frequency of the cantilever probe in contact with the sample.

Optionally, certain methods of this aspect further comprise 15 the step of controlling the force on the cantilever probe. In one embodiment, the step of controlling the force on the cantilever probe comprises providing a change in frequency, a 20 change in magnitude or both changes in frequency and magnitude of the current passing through the self-heating cantilever probe.

In another aspect, provided are other methods of operating 25 a probe microscope, for example to characterize a region of a sample with sub-micron spatial resolution. A specific method of this aspect comprises the steps of: interacting a probe tip of a cantilever probe with a surface of the sample; providing a magnetic source that creates a magnetic field in proximity to the cantilever probe; passing a current through the cantilever probe so as to generate a force on the cantilever probe due to 30 an interaction between the current and the magnetic field, wherein the cantilever probe comprises two substantially parallel conductive arms and a conductive end region; and measuring a signal indicative of the motion of the cantilever. 35 Optionally, the current comprises an alternating current at one or more frequencies, thereby generating an oscillatory force on the cantilever probe.

In one embodiment, a method of this aspect further comprises the step of repeating the passing and measuring steps at 40 a plurality of frequencies and measuring a frequency dependent response of the cantilever probe interacting with the sample surface. Another method of this aspect further comprises the step of determining a contact resonant frequency of the cantilever probe in contact with the sample.

In another aspect, provided is an apparatus for characterizing 45 a region of a sample with sub-micron spatial resolution. Apparatuses of this aspect are useful, for example, in the foregoing methods. An embodiment of this aspect comprises: a cantilever probe comprising an integrated heater and a probe tip; a magnetic source positioned proximate to the cantilever probe; an AC current source positioned in electrical communication with the cantilever probe, the AC current source for driving a current through the integrated heater of the cantilever probe to generate a Lorentz force on the cantilever probe; and a deflection measurement system positioned 50 to measure a signal indicative of an oscillatory motion of the cantilever probe. Optionally, the cantilever probe comprises two substantially parallel arms.

Optionally, embodiments of this aspect further comprise 55 additional components. For example, an embodiment further comprises a DC current source positioned in electrical communication with the cantilever probe, the DC current source for driving current through the integrated heater of the cantilever probe to adjust the static temperature of the cantilever probe. Optionally, an embodiment further comprises a demodulator positioned in electrical communication with the deflection measurement system, the demodulator for deter-

mining a property of the oscillatory motion of the cantilever probe, wherein the property is selected from the group consisting of: amplitude, phase, frequency and any combination of these.

Optionally, an embodiment further comprises a self-resonance tracker positioned in electrical communication with the deflection measurement system and the AC current source, the self-resonance tracker for adjusting a frequency of AC current through the integrated heater of the cantilever probe to maintain the oscillatory motion substantially at a resonant frequency of the cantilever probe. In one embodiment, the self-resonance tracker adjusts a frequency of AC current to a contact resonant frequency of the cantilever.

In one embodiment, the cantilever probe further comprises two substantially parallel arms. Optionally, the magnetic source is arranged substantially parallel to the length of the two substantially parallel arms. In a specific embodiment, Lorentz forces in the two substantially parallel arms substantially cancel such that that a primary net force on the cantilever probe occurs at a tip end of the cantilever probe.

In another aspect, provided are devices for characterizing a region of a sample with sub-micron spatial resolution. In a specific embodiment, a device of this aspect comprises: a self-heating cantilever probe having a tip; a magnetic source placed in proximity to the cantilever probe; and a current source in communication with the self-heating cantilever. Optionally, the self-heating cantilever probe having a tip comprises a cantilever probe described above. In one embodiment of this aspect, the device further comprises a deflection measurement system and a demodulator. In an embodiment of this aspect, the device further comprises a resonance tracker to determine a resonance of the self-heating cantilever probe.

In embodiments, the magnetic source comprises a permanent magnet coupled to a magnetic pole piece. Useful magnetic pole pieces include those having a permeability of more than 10,000, a permeability of more than 20,000, a permeability of more than 30,000, a permeability of more than 40,000, a permeability of more than 50,000, a permeability of more than 100,000, a permeability of more than 150,000, a permeability of more than 200,000 or a permeability of more than 250,000. In embodiments, the permeability of a magnetic pole piece refers to the relative permeability of the magnetic pole piece. Optionally, the magnetic source and the magnetic pole piece generate a magnetic field having a strength of at least 0.2 T at the self-heating cantilever probe. Optionally, the magnetic source and the magnetic pole piece generate a magnetic field having a strength of at least 0.4 T at the self-heating cantilever probe.

In embodiments, the magnetic source comprises a magnet, such as a permanent magnet. Optionally, the magnet is positioned on or in a slot, thereby permitting sliding the magnet between at least two locations, such as two locations comprising (a) a first location to maximize the magnetic field at the self-heating cantilever probe and (b) a second location to permit exchanging or removal of the self-heating cantilever probe.

In embodiments, for example, the current source is configured to ramp the self-heating cantilever probe through a plurality of temperatures. Optionally, the current source is configured to include an AC current component that generates an oscillating force on the self-heating cantilever probe. Optionally, the current source is configured to generate AC currents over a plurality of frequencies. Optionally, AC currents generated at a plurality of frequencies are used to create a spectrum of the self-heating cantilever probe response versus frequency. In an exemplary embodiment, the spectrum of the

self-heating cantilever probe response versus frequency is substantially devoid of parasitic mechanical resonances. In one embodiment, the current source is configured to generate currents comprising an AC frequency component in excess of 1 GHz. Optionally, the self-heating cantilever probe exerts a force on a sample at a frequency in excess of 1 GHz.

Devices of this aspect optionally further comprise a system for calculating one or more properties of the self-heating cantilever probe or the sample. Useful systems for such calculations include those comprising a computer, a CPU, a digital signal processor, a floating point gate array or other digital computation means. In a specific embodiment, a device of this aspect further comprises a system for calculating one or more viscoelastic properties of a sample based on a resonance of the self-heating cantilever probe. In a specific embodiment, a device of this aspect further comprises a system for calculating a plastic deformation property of a region of a sample based on a resonance of the self-heating cantilever probe. Useful plastic deformation properties include a yield strength of the sample, a hardness of the sample and a creep of the sample. In a specific embodiment, a device of this aspect further comprises a system for calculating of one or more glass transition temperature properties of a region of a sample based on a resonance of the self-heating cantilever probe.

In another aspect, provided are methods for determining a property of a sub-micron region of a sample. A specific method embodiment of this aspect comprises the steps of: interacting a probe tip of a self-heating cantilever probe with a surface of the sample; applying a force between the probe tip and the surface of the sample, wherein the force is generated by an interaction between a current through the self-heating cantilever probe and a magnetic field; measuring a response of the self-heating cantilever probe to the applied force; and determining the property of a sub-micron region of the sample from the measured response. Self-heating cantilever probes useful with methods of this aspect include those described above. In embodiments, methods of this aspect further comprise repeating the interacting, applying, and measuring steps at a plurality of locations of the surface of the sample.

Optionally, the property determined using a method of this aspect comprises a property of a sub-micron region of a sample comprising at least one of plastic deformation, a yield strength, hardness, creep, glass transition temperature, melting temperature, viscoelastic property (storage/loss modulus, $\tan(\delta)$) and stiffness.

In some embodiments, a method of this aspect further comprises a step of heating at least the sub-micron region of the sample by passing a current through the self-heating cantilever probe. Optionally, the step of heating at least the sub-micron region of the sample occurs during the step of applying a force between the probe tip and the surface of the sample. In various embodiments, a method of this aspect further comprises repeating the interacting, applying, measuring and heating steps one or more times to measure a response of the self-heating cantilever probe at a plurality of temperatures of the sub-micron region of the sample.

Useful responses of the self-heating cantilever probe include, but are not limited to, those comprising one or more of a deflection, contact resonance frequency, amplitude, phase, in-phase amplitude (X), and quadrature amplitude (Y) of the self-heating cantilever probe.

Without wishing to be bound by any particular theory, there can be discussion herein of beliefs or understandings of underlying principles relating to the invention. It is recognized that regardless of the ultimate correctness of any

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mechanistic explanation or hypothesis, an embodiment of the invention can nonetheless be operative and useful.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified schematic diagram of Lorentz actuation of a self-heated cantilever.

FIG. 2 shows periodic deflection of a cantilever in response to Lorentz force and thermomechanical actuation.

FIG. 3a shows periodic Lorentz and thermomechanical deflections of a cantilever versus AC current applied to it.

FIG. 3b shows static temperature rise and periodic temperature of a cantilever with an AC current at resonance.

FIG. 3c shows periodic temperature and thermomechanical deflection of a cantilever versus the heating frequency.

FIG. 4 is an intermittent contact (“tapping”) mode image on a calibration grating by a Lorentz-force actuated cantilever.

FIG. 5 shows maps of cantilever deflection at resonance for Lorentz force actuation in different magnetic orientations.

FIG. 6a shows theoretical magnetic field lines surrounding the center axis of a magnet.

FIG. 6b shows theoretical and measured forces exerted on a cantilever above the magnet shown in FIG. 6a.

FIG. 7 shows the force induced by different directions of magnetic field.

FIG. 8 shows nanothermal analysis by measuring cantilever contact resonant frequency as a function of tip-sample temperature on a highly filled epoxy.

FIG. 9 show measurements of glass transitions on a thin film <100 nm thick.

FIG. 10 shows a contact resonance image of a filled epoxy obtained using Lorentz force actuation with a self-heated probe

FIG. 11 shows an AFM image of a highly filled epoxy and measurements of contact resonance and glass transition temperatures in the vicinity of a filler particle.

FIG. 12 shows a flow diagram of a method of measuring temperature and frequency dependent properties of a sample using a self-heating cantilever.

FIG. 13 shows a plot of cantilever response to Lorentz force as a function of frequency and temperature on a highly crystalline polymer.

FIG. 14 shows the creation of a master curve using time-temperature superposition.

FIG. 15 shows the extraction of energies from time temperature superposition.

FIG. 16 shows a distribution of Lorentz forces on a self-heated cantilever resulting in the cancellation of net forces in the parallel arms and the center of net force near the tip end of the cantilever.

FIG. 17 is an illustration of the force distribution for Lorentz force actuation under an embodiment of the current invention versus the prior art.

FIG. 18 is an illustration of one embodiment for repeated adjustment of DC force and measurement of dynamic response of a cantilever.

FIG. 19 is an illustration of an alternate embodiment for repeated adjustment of DC force and measurement of dynamic response of a cantilever.

FIG. 20 is an illustration of the extraction of material properties and tip-sample forces from a measurement of the cantilever response.

FIG. 21 shows the variation in DC force as a function of temperature under the prior art versus an embodiment of the current invention.

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FIG. 22 shows (a) a schematic of magnetic fields and the cantilever with oscillating current on it; (b) scanning electron microscope (SEM) image of the cantilever used in an experiment.

5 FIG. 23 shows data providing static and periodic temperature of a cantilever versus power.

FIG. 24 shows static cantilever behaviors due to the Lorentz force and thermomechanical bending including the static deflections versus the temperature rise. Inset shows that 10 the Lorentz deflection is linearly proportional to the applied current.

FIGS. 25A and 25B show schematic diagrams of cantilever probe embodiments.

FIG. 26 provides data showing the results of magnetic field 15 strength modeling on a cantilever probe embodiment.

FIG. 27 provides data showing resonant frequencies of two cantilever probe embodiments.

FIG. 28A provides data showing height measurements 20 obtained using a cantilever probe embodiment. FIGS. 28B and 28C provide data showing broadband mechanical spectra obtained using a cantilever probe embodiment.

FIGS. 29A, 29B and 29C provide data showing Lorentz contact measurements obtained using a cantilever probe embodiment. FIG. 29D provides data showing mechanical 25 spectra obtained using a cantilever probe embodiment.

FIG. 30 provides data showing broadband mechanical spectra obtained at various temperatures using a cantilever probe embodiment.

FIG. 31 provides data illustrating composition mapping 30 using Lorentz contact resonance obtained using a cantilever probe embodiment.

FIG. 32 provides data showing Lorentz contact measurements obtained using a cantilever probe embodiment.

FIG. 33 provides data showing mechanical spectra 35 obtained using a cantilever probe embodiment.

FIG. 34 provides data illustrating relative stiffness as a function of contact resonance for cantilever probe embodiments.

DETAILED DESCRIPTION

In general the terms and phrases used herein have their art-recognized meaning, which can be found by reference to standard texts, journal references and contexts known to those skilled in the art. The following definitions are provided to clarify their specific use in the context of the invention.

“Thermal contact” and “thermal communication” are used 45 synonymously and refer to an orientation or position of elements or materials, such as a heater-thermometer and a conductive tip, such that there is more efficient transfer of heat between the two elements than if they were thermally isolated or thermally insulated. Elements or materials may be considered in thermal communication or contact if heat is transported between them more quickly than if they were thermally isolated or thermally insulated. Two elements in thermal communication or contact may reach thermal equilibrium or thermal steady state and in some embodiments may be considered to be constantly at thermal equilibrium or thermal steady state with one another. In some embodiments, elements in thermal communication with one another are separated from each other by a thermally conductive material or intermediate thermally conductive material or device component.

In some embodiments, elements in thermal communication with one another are separated by a distance of 1 μm or less. In some embodiments, elements in thermal communication with one another are also provided in physical contact. 55

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"Electrical contact" and "electrical communication" refers to the arrangement of one or more objects such that an electric current efficiently flows from one object to another. For example, in some embodiments, two objects having an electrical resistance between them less than 100Ω are considered in electrical communication with one another. An electrical contact can also refer to a component of a device or object used for establishing electrical communication with external devices or circuits, for example an electrical interconnection. "Electrical communication" also refers to the ability of two or more materials and/or structures that are capable of transferring charge between them, such as in the form of the transfer of electrons. "Electrical communication" also refers to a configuration of two or more components such that an electronic signal or charge carrier can be directly or indirectly transferred from one component to another. In some embodiments, two components in electrical communication are in data communication, such that a signal value or digital data can be exchanged between the two components. As used herein, electrical communication includes one way and two way electrical communications. In some embodiments, components in electrical communication are in direct electrical communication wherein an electronic signal or charge carrier is directly transferred from one component to another. In some embodiments, components in electrical communication are in indirect electrical communication wherein an electronic signal or charge carrier is indirectly transferred from one component to another via one or more intermediate structures, such as circuit elements, separating the components.

"Cantilever" refers to a structure having at least one fixed, or attached end, such as a microcantilever of an atomic force microscope or nano-materials sensor. Cantilevers include microcantilevers and nanocantilevers having a free ended cantilever configuration or having a clamped-clamped cantilever configuration. A cantilever generally comprises a tip, for example useful for probing properties of a surface, such as contours, morphology, composition, etc. In some embodiments, microcantilevers have dimensions on the order of 1 to 1000 μm . Useful cantilevers comprise those having any useful shape, including platform or rectangular shaped cantilevers, circular shaped cantilevers, ladder shaped cantilevers, U-shaped cantilevers, triangular shaped cantilevers, and cantilevers having cutout portions. "Rectangular cantilever" specifically refers to a cantilever having a platform type shape, with a length, a width and a height. Rectangular cantilevers also include embodiments where there are one or more cutout portions. For some embodiments, a "cutout portion" refers to a region of a cantilever where material is removed from a cantilever that would be an otherwise monolithic body. For specific embodiments, a cutout portion refers to regions within a cantilever that comprise air or other material which do not allow efficient coupling and/or substantial coupling of mechanical or thermal energy from one portion of a cantilever to another portion of a cantilever.

"Fixed end" or "fixed base" refers to an end of a cantilever which is attached to the cantilever base. A fixed end of a cantilever is unable to move independently of the cantilever base.

"Free end" or "non-fixed end" refers to an end of a cantilever which is not attached to the cantilever base. The free end of a cantilever is able to move independently of the cantilever base, for example when the cantilever bends or vibrates. For some embodiments, when a cantilever is operating in contact mode, the free end of the cantilever or the tip of the cantilever is in contact with an object, such as a surface; in these embodiments the free end is coupled to the sample. For embodi-

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ments, when a cantilever is operating in tapping mode, the free end of the cantilever is permitted to vibrate.

"Tip end" refers to an end of a cantilever at which a probe tip of the cantilever is located. In embodiments, a tip end of a cantilever is a free end of a cantilever.

"Heater-thermometer" refers to a combination of a device for determining temperature and a device for actuating the temperature. In an embodiment, a thermistor is useful as a heater-thermometer. A thermistor refers to a resistive material which has a resistance which is temperature dependent. Providing a current or voltage to a thermistor can result in an increase in the temperature of the thermistor through resistive heating. Since the resistance of a thermistor is temperature dependent, it can be used as means for measuring the temperature; i.e., by measuring the resistance of the thermistor, the temperature of the thermistor can be determined. A thermistor useful with some embodiments of the present invention comprises doped silicon, for example silicon doped with a phosphorus concentration of about $1\times 10^{15} \text{ cm}^{-3}$ to $1\times 10^{18} \text{ cm}^{-3}$. A heater-thermometer can refer to a single or separate distinct elements for measuring and actuating the temperature, for example a thermistor or a thermocouple and a resistive heater.

"Self-heating" refers to the ability of a device to generate heat within the device itself. In an embodiment, a device is self-heating if a heating element is integrated as a component of or within the device. In a specific embodiment, self-heating refers to the ability of a device to control its own temperature by generation of heat within the device. For example, in an embodiment, a self-heating device can maintain a temperature of the device within a specified temperature window over a specified period of time. In another embodiment, self-heating refers to the ability of a device to generate an amount of heat in the device sufficient for heating the device to a specified temperature within a specified period of time. In embodiments, a self-heating device can change the temperature of the device by a specified amount within a specified period of time. For example, in an embodiment, a self-heating device ramps the temperature of the device at a rate of more than 100° C./minute. In one embodiment, the term self-heating refers to a device especially configured for generation of heat within the device and is intended to distinguish with devices in which heat generation is minimal or is ancillary to or adverse to the primary function of a device.

"Piezoelectric" refers to a material exhibiting a piezoelectric property. Piezoelectric properties include, but are not limited to, the ability to generate a voltage and/or a current upon the application of a mechanical stress and/or change of an applied mechanical stress. Piezoelectric properties include, but are not limited to, the ability to change physical dimensions and/or the state of strain upon the application of a voltage and/or a current.

"Positioned proximate to" refers to the position of a device component relative to another device component or feature.

In an embodiment, proximate to refers to the arrangement of one device component such that it is within 100 μm of another device component or feature, optionally for some applications within 10 μm of another device component or device feature, and optionally for some applications within 1 μm of another device component or device feature. In some devices of the invention, the heater-thermometer is positioned proximate to the free end of the cantilever. In some embodiments, the phrase "magnetic field in proximity to a cantilever probe" refers to the relative position of a cantilever and a magnetic field such that the cantilever is present within the magnetic field. For example, in one embodiment, a magnetic field in proximity to a cantilever probe refers to the position of a

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cantilever probe within a magnetic field or the position of a cantilever probe such that a current passing through a cantilever probe exhibits a force on the cantilever probe due to the interaction between a current flowing through the cantilever probe and the magnetic field. In embodiments, a cantilever probe is positioned at a distance less than 5 mm, less than 2 mm or selected in the range of 1-2 mm from the surface of a magnetic source producing a magnetic field.

"Magnetic source" refers to a device, material or element that produces, is capable of producing or configured for producing a magnetic field. In one embodiment, a magnetic source refers to a permanent magnetic material. In one embodiment, a magnetic source refers to an electromagnet. Useful magnetic sources include those having any shape, for example a cube shape, a disc shape, a cylindrical shape, a bar shape, a horseshoe shape. In embodiments, a magnetic source is comprised of multiple magnetic sources. In embodiments, useful magnetic sources include those having a dimension, for example a lateral dimension, a thickness dimension or a diameter, of 1 mm, of 2 mm, of less than 12 mm, selected over the range of 1-12 mm, selected over the range of 2-12 mm or selected over the range of 6-12 mm.

"Piezoresistive sensor" refers to a resistive material having resistance which changes when a strain is induced in the material, for example when the material is stretched or compressed. A piezoresistive sensor useful with some embodiments of the present invention comprises doped silicon, for example silicon doped with phosphorus or boron. In some embodiments of the present invention, piezoresistive sensors are integrated into a cantilever near the fixed end, and are useful for sensing surface stresses induced in the cantilever. According to this aspect, when a surface stress is induced in a cantilever which has an integrated piezoresistive sensor, the resistance of the piezoresistive sensor will change and can be sensed by a resistance sensing circuit thereby sensing the surface stress of the cantilever.

"Sense" and "sensing" refer to determination and/or observation of a signal indicative of a value, variable and/or property. In some embodiments, sensing refers to direct measurement of a value, variable and/or property; in other embodiments, sensing requires transformation (e.g., a mathematical transformation) to convert one value, variable and/or property into a measured and/or detected value.

"Measure" and "measuring" refer to determination of an absolute or relative value of a variable and/or property.

"Detect" and "determine" refer to observation and/or measurement of a property, object or value and/or a change in a property, object or value.

"Deflection" refers to motion of one object, such as a bending or elastic deformation. Deflection may comprise static motion, transient motion and/or vibrational motion, for example due to a force and/or the presence of another object.

"Aligned" refers to the relative orientation between two or more objects, fields, or axes. In an embodiment, two or more objects, fields or axes are aligned if the objects, fields or axes are parallel. The term "substantially aligned" refers to the condition where two or more objects, fields or axes have alignment sufficiently close to absolutely aligned so as not to negatively impact operation of a device requiring alignment. In an embodiment, two or more objects, fields or axes are substantially aligned if their alignment is less than 15° from absolutely aligned, less than 10° from absolutely aligned or less than 5° from absolutely aligned.

"Submicron region" refers to a portion of an object that has at least one characteristic dimension less than 1 micrometer. For example, a 900 nm spherical domain in a composite sample comprises a submicron region. Submicron regions

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may also be as small as a few nanometers or less. In some embodiments, a submicron region refers to the portion of an object or surface in contact with the tip of a microcantilever and that portion of the object or surface immediately surrounding the portion in contact with the tip.

"Contact mode" refers to a mode of operation of an atomic force microscope or microcantilever where the microcantilever tip is generally maintained in contact with a surface.

"Flexural mode" refers to a characteristic vibrational bending mode of a microcantilever which oscillates at a characteristic frequency. A flexural mode can refer to the first order or a higher vibrational mode of a microcantilever. "Contact mode flexural mode" refers to a characteristic vibrational mode of a microcantilever having a tip which is maintained in contact with a surface. The contact mode flexural modes and the free flexural modes (non-contact flexural modes) of a microcantilever are generally different and oscillate with different characteristic frequencies. In some embodiments, a contact flexural mode depends on the mechanical properties of the sample that is in contact with the tip of a microcantilever.

"Quality factor" or "Q" refers to a measure of the sharpness of an oscillatory resonance, for example a flexural oscillation of a cantilever. The Quality factor is generally defined to be the resonant frequency divided by the width of the resonance at half the maximum energy, i.e. $Q = f_0/\Delta f$.

"Substantially independent" refers to the ability of one object to behave, move, or otherwise perform a function without being affected by or with reduced effects from another object.

"Substantially within" refers to containment of one object within the bounds of another object.

"Spatially resolved map" refers to a spatial plot showing position dependent variations, for example position dependent variations in a property.

"Viscoelastic response" refers to a measure of a frequency dependent strain or deformation induced in a material in response to a stress applied to the material.

"Thermal transition temperature" refers to a temperature at which a material undergoes a significant change in material properties, for example, a change in elasticity, damping, thermal expansion and other properties. Thermal transitions include softening, melting, solidifying and glass transitions.

"Interacting a probe tip . . . with a sample" refers to positioning the probe tip of a cantilever probe in sufficient proximity with a surface such that it can sense and/or induce a force between the probe tip and the a sample. Such interaction can be attractive, repulsive, or a combination of both. The interaction forces can include but are not limited to coulomb repulsion, Van der Waals, electrostatic, meniscus, hydrophobic, and others. The probe-tip interaction can be continuous contact, intermittent contact, tapping, non-contact, modulated force, and/or pulsed force, for example.

FIG. 1 shows a simplified schematic diagram of one embodiment of the invention. A self-heatable cantilever probe 101 with a tip 105 is interacted with a sample 102. An excitation source 104 provides any desired combination of DC excitation (V_{DC}) and AC excitation (V_{AC}) to cause current to flow through the cantilever. The excitation source may be a voltage source and/or a current source. The DC and AC components may be synthesized separately and summed using any suitable analog circuitry (e.g. op-amps, transistor circuits and/or AC coupling nodes) or may be added digitally and generated together in the same digital-to-analog converter. The system can also be operated with only AC or only DC excitation.

The resulting sum of any AC and DC excitation is applied across the cantilever to create currents I_1 and I_2 through the cantilever arms **103** and current I_3 through an end region **106** near the tip end of cantilever **101**. (The magnitudes of these currents are substantially the same, but the directions are different, as indicated by the arrows.) A magnetic field B (**108**) is applied to interact with the current flowing through the cantilever to induce a Lorentz (electromagnetic) force on the cantilever. The magnetic source for the B field may be a permanent magnet or an electromagnet. In a preferred embodiment, the magnetic source can be a permanent magnet of rare earth materials, for example NeFeB or SmCo magnets. For variable temperature measurements, a resistive heater region **107** can be included in the end region **106** of the cantilever to form a self-heatable cantilever. Alternately, the probes can be formed without a resistive heater to allow high currents with minimal change in the cantilever probe temperature. In this case, the end region is selected to be conductive instead of resistive.

The Lorentz force vector F_n for a given current segment is given by $F_n = L_n (I_n \times B)$, (where L_n is the length of the current segment, I_n is the current vector and "x" in this case indicates the cross product.) Thus the magnitude of the force is $F = I_n L_n B \sin \theta$, where θ is the angle between the current segment and the magnetic field. For the strongest Lorentz force applied to the cantilever, the magnetic field B is substantially perpendicular with the current path I_3 , as shown in FIG. 1. That said, the magnetic field can be oriented somewhat off axis for convenience of the design with a proportional loss in the generated force. It is worth noting that in the design shown in FIG. 1, the force is primarily generated at the end of the cantilever near the tip, as indicated by force arrow **110**. In the case that the magnetic field is oriented perpendicular to the current segment I_3 , the force on the cantilever legs **103** is zero due to the fact that the sine term is zero in both cases ($\theta=180^\circ$ and $\theta=0^\circ$). Even in the case that the magnetic field has components in other directions, the forces interacting with I_1 and I_2 are equal but opposite in direction. Thus in this embodiment the force contributions of I_1 and I_2 in the direction of cantilever flexion cancels each other. The resulting force is substantially from the current segment I_3 from near the tip end of the cantilever. This is in contrast to V-shaped cantilevers where the current vectors are not in opposite direction. In this case the force is applied over the entire length of the cantilever. The implications of this are discussed below.

Detection of cantilever motion. A signal indicative of the cantilever motion is generally recorded to measure a property of the sample. There are many techniques used for measuring motion of the cantilever. The most common method involves the use of the optical lever technique, where a light beam is reflected off a portion of the cantilever and the position of the reflected light beam is recorded using a position sensitive detector or a multiple segment photodiode. Other techniques include interferometric, capacitive, inductive, piezoelectric, and piezoresistive readout schemes. One scheme that is particularly appealing with self-heated probes is to measure the heat flow from the heater region by measuring the heater resistance. The heat transfer changes as a function of cantilever/sample separation and this feature has been used to measure the motion of the cantilever and variations in sample topography. In any case, any of the methods above can be used to generate a signal indicative of the motion of the cantilever. This signal can indicate the deflection, position, velocity, oscillation amplitude, phase, frequency and/or other properties of the motion of the cantilever.

Deflection spectra versus power and frequency. FIG. 2 shows examples of using the Lorentz force to excite self-heatable cantilevers for both free excitation (FIGS. 2a-b) and a contact resonance (FIG. 2c). FIGS. 2a-b also shows the thermomechanical excitation that appears at 2 \times the drive frequency. FIGS. 2a-c show the cantilever deflection amplitude with 1 mA sinusoidal current $I \sin [2\pi(f/n)t]$, where $f=\omega/2\pi$ is the frequency of the periodic current. The Lorentz data is for $n=1$, because the Lorentz actuation has the same frequency as the current oscillation. The thermomechanical actuation is for $n=2$, since the thermomechanical response is at twice the current frequency. All of the periodic values reported are amplitude, which is half of the peak-to-peak value.

In these experiments, the cantilever thermal time constant is the time for heat to diffuse from the cantilever heater through the length of the legs, which is about 100 μ sec for the present cantilevers. FIG. 2(a) shows that below the cantilever thermal time constant, both periodic thermomechanical and Lorentz deflections are nearly constant, and are close to the static deflection. The static thermomechanical deflection is two times larger than the periodic deflection amplitude, since the thermomechanical deflection always occurs in one direction regardless of the current direction, making the deflection amplitude half of the maximum deflection. As the actuation frequency increases, the cantilever deflection by Lorentz force does not show a distinct frequency dependence. However, the thermomechanical deflection decreases significantly when the actuation frequency exceeds the cantilever thermal time constant. The Q factor of the silicon cantilever was 66, and so the relatively low dissipation in the cantilever allows for the Lorentz actuation to increase significantly near the resonance frequency. At mechanical resonance, the periodic Lorentz deflection is 1000 \times higher than the periodic thermomechanical deflection. The thermomechanical deflection is relatively small because the cantilever is made of single crystal silicon that induces little bimaterial deflection. Also, since the heater is located at the cantilever free end, the cantilever is not uniformly heated. Hence, the cantilever actuation at the resonance is primarily induced by Lorentz force.

As the Lorentz and thermomechanical deflections are governed by current and temperature, the two deflection mechanisms are compared to examine the crosstalk between them. The temperatures reported here are the heater temperatures at the cantilever end, which is larger than the temperature in the cantilever legs or the cantilever base. The tip-sample temperature is also lower than the cantilever heater temperature.

FIG. 3(a) shows the periodic Lorentz and thermomechanical deflection as a function of the periodic current. FIG. 3(b) shows the static temperature rise above room temperature and the periodic temperature oscillation at mechanical resonance. With AC current of 0.2 mA, the periodic Lorentz deflection is 75 nm at resonance, sufficiently high for imaging, and with minimal DC temperature rise. It is possible to achieve larger amplitudes as well, which have higher DC temperature. Since the dissipated power is I^2R (where I is the current and R is the probe resistance), operating at twice the current and twice the Lorentz deflection leads to 4 \times the power dissipation and roughly 4 \times higher static temperature increase. For example, at current of 1 mA, it is possible to achieve 336 nm of Lorentz deflection, but with a temperature rise of 86° C.

The static and periodic temperatures are quadratic with the current and linear with cantilever power. The cantilever thermal conductance is estimated as 1.6×10^5 W/K. A 1 mA DC current causes a static temperature rise of 172° C. and static thermomechanical deflection of 38 nm. When 1 mA AC current is applied at mechanical resonance for Lorentz actuation,

it generates a periodic temperature of 2° C. and negligible thermomechanical deflection. This small periodic response is because the mechanical resonance frequency is larger than the cantilever thermal time constant.

FIG. 3(c) shows the periodic temperature and corresponding periodic thermomechanical deflection of cantilever as a function of the heating frequency, which is twice the current frequency. At thermomechanical resonance, the periodic temperature variation is only 3.5° C. and the periodic thermomechanical deflection is 0.32 nm, whereas the periodic Lorentz deflection is 10.5 nm at the same frequency. Note that the periodic thermomechanical deflection follows the periodic temperature quite well, and is still quadratic for current rather than linear as seen in FIG. 3(a). Both of them imply negligibly small harmonic artifacts of the Lorentz actuation. That is, the Lorentz deflection is quite close to pure harmonic oscillation.

The usefulness of the actuation scheme was demonstrated by imaging a calibration grating using Lorentz actuation. A silicon grating having 20 nm tall features was placed on the magnet, and the cantilever was powered with small AC current of 0.2 mA supplied from internal function generator of the AFM. In standard amplitude modulation (“tapping”) mode, this function generator drives the piezoelectric oscillator on the cantilever holder. Thus an imaging feedback loop with the Lorentz actuation was able to be fully implemented. FIG. 4 shows the image acquired from this experiment. Even with such a small current, the Lorentz deflection is sufficient and the image shows no difference compared to the normal piezo-driven imaging. While the cantilever position is monitored using standard laser-based deflection, it is expected that the temperature signal of the heated cantilever could also be used to detect the substrate, as has been demonstrated previously for amplitude modulation imaging.

Influence of field direction on Lorentz force. The direction of the magnetic field is critical for Lorentz actuation. Here, the effect of the magnet field direction on Lorentz force is investigated by changing the cantilever location relative to the magnet, and also by changing the magnet orientation. The cantilever was placed 200 μm above the 3 mm cube magnet and powered by 0.2 mA sinusoidal current. The cantilever deflection was measured as a function of lateral position, resulting in a 2D map of cantilever periodic deflection with 100 μm spatial resolution.

FIGS. 5a-5c show the 2D deflection maps above a cube magnet for different magnet orientations (O1, O2, O3). The same experiment was also performed above a circular disk magnet (O4), FIG. 5d. For a magnetic orientation of a vertically aligned poll (O1 and O4), the maximum cantilever deflection is achieved when the cantilever is near the edge of the magnet where the B_x is maximized. Also, there is zero-deflection region, where the forces by B_x and B_z are canceled out. FIG. 5(d) shows the maximum deflection along the magnet edge more clearly. For O2, which corresponds to the magnetic pole aligned parallel to the cantilever, the periodic deflection is uniform except at the edge of the magnet, since B_z is the dominant magnetic field direction with this magnet orientation. This is the orientation used to measure the deflection spectra and imaging presented above, since the uniform periodic deflection reduces error with respect to the cantilever position. For the magnet oriented at O3, there was no cantilever deflection along the center line ($y=0$) because B_y is the only dominant magnetic field and it does not induce the cantilever deflection as seen Eq. (3).

FIG. 6(a) shows the calculated magnetic field around the cube magnet with vertical pole (O1), on the xz plane ($y=0$). FIG. 6(b) shows the calculation and measurement of the Lorentz force with vertical and horizontal magnetic field (O1,

O2), which compare very well. The field strengths of the magnet used to fit the experiment and calculation are different for each magnet orientation, 0.41 T for O1 and 0.26 T for O2. The Lorentz force with the O3 magnet orientation is zero in both calculation and measurement.

FIG. 7 shows the force induced by each magnetic field direction, clearly indicating how the Lorentz force depends upon the magnetic field direction and magnet orientation. As predicted from Equations (3) and (5), B_x dominates the Lorentz force acting on the cantilever. The force induced by the magnetic field gradient is very small and not plotted here.

Detecting material softening by Lorentz nanoTA. As an application of Lorentz force actuation, nanoscale thermal analysis (nanoTA) was performed to measure the glass transition temperature T_g via the temperature-dependent shift of contact resonance frequency. NanoTA works by detecting a slight penetration of the tip into the sample at T_g , while increasing the tip temperature. A challenge with the method is that it can be hard to measure T_g for highly filled or highly cross-linked materials, because the softening near T_g can be small and the thermal expansion near T_g can be large enough to counteract the softening. However, by sensing the resonance frequency shift instead of deformation, it is possible to detect material softening independent from substrate thermo-mechanical expansion.

The measurement was done on four randomly selected regions of a nonconducting underfill epoxy (CHIPCOAT U8437-2, NAMICS Corporation). This is a highly filled epoxy (~50% by weight with 2-10 μm silica particles) that improves the mechanical and thermal performance of the material, but whose presence increases the difficulty of the conventional nanoTA method. A small printed circuit board with a sample of the epoxy was placed on a 12.7 mm×1 mm thick NdFeB disk magnet such that the region of interest on the sample was at the outer diameter of the magnet, where the Lorentz deflection is maximum.

For this experiment, a commercial self-heating AFM cantilever was used (AN200, Anasys Instruments), which is very similar to the cantilever of the previous experiments. The cantilever was periodically approached to the surface to determine the point of contact with the sample. After each tip approach, the cantilever was moved to a selected loading force and then a chirp waveform (2V_{pp} AC) was applied across the legs of the cantilever. DC voltage was applied across the heater to ramp the probe temperature from just over ambient to above the glass transition temperature. Approach curves were repeated during this process to ensure a constant loading force as the temperature was ramped. FIG. 8 shows the contact resonance frequency versus the temperature at the tip, indicating the peak of the resonance frequency corresponding to the T_g . The T_g specified by the manufacturer (137° C.) is close to the average T_g observed in the measurements, however, the contact resonance nanoTA measurements show local variations not observable in bulk T_g measurements.

The contact resonance frequency can be determined by a variety of means, including a lock-in amplifier or other demodulator. A demodulator can create a signal that may be indicative of the amplitude, phase, in-phase component (X), quadrature component (Y), or similar measurements of the cantilever's AC motion. The demodulator may comprise an RMS-to-DC converter, a lock-in amplifier, and/or a Fast Fourier Transform or other demodulation means that extract oscillation amplitudes at one or more frequencies. The demodulator may be implemented in analog electronics, digital electronics, and/or implemented in software. In the case of a software implementation, the demodulator may be pro-

grammed on an embedded controller, a digital signal processor, a field programmable gate array, other programmable logic devices, and/or a personal computer. The demodulator may also have its functions distributed across multiple hardware and software platforms.

In one embodiment a resonant peak frequency can be identified by analyzing an amplitude versus frequency curve. A peak frequency can be found by determining a maximum amplitude response in a range of frequencies, or by fitting a model through a portion of the amplitude versus frequency curve. For example, one can fit a Lorentzian function, a Gaussian function or any number of peak shaped functions. With high signal to noise, small numbers of data points can be used for peak fitting. For example, very efficient algorithms can be used to detect peak frequencies with resolution below the FFT bin size using a Gaussian or parabolic peak fit through the three highest points, as described for example in U.S. Pat. No. 6,965,068. These techniques have the advantage of being computationally very efficient with no requirement for iterative curve fitting. Another method of determining the contact resonance frequency with high noise rejection is to employ a peak centroid measurement. In one implementation, one can determine a centroid frequency where the integral from a start frequency to the centroid frequency has half the area of the integral from a start frequency to an end frequency. This technique can provide useful measurements of the contact resonance frequency and its trends with temperature even when the individual frequency response measurements may be too noisy to determine a contact resonance frequency from the maximum cantilever response amplitude. The peak frequency, f_r , can also be determined by selecting a frequency with a desired phase (e.g. when the phase crosses 90°).

Polymer Films <100 nm thick. FIG. 9 shows a measurement of the glass transition of a thin photoresist film obtained by measuring the contact resonance as a function of temperature using a self-heating AFM cantilever probe. The photoresist sample is 50-100 nm thick, below the level of detection of conventional nanothermal analysis. In this case, as the material softens and allows the tip to penetrate into the sample, the contact resonance frequency increases. This is due to the fact that the tip becomes closer to the underlying silicon substrate which is much harder than the polymer. Seeing glass transitions on thin films with conventional nanothermal analysis can be difficult to impossible because the small amount of sample material provides insufficient thermal expansion to create a DC deflection of the cantilever sufficient to be readily measured and tracked as a function of temperature.

Lorentz force excitation can be used to map spatial variations in sample stiffness in heterogeneous samples. FIG. 10 shows a map of AFM surface topography and stiffness via contact resonance on a highly filled polymer epoxy. The epoxy has small silica particles that show up as brighter spots in the AFM image (top). The center image is a “deflection” or “error signal” image that highlights the fine features of the sample. The bottom image is a contact resonance image obtained with Lorentz force actuation with a self-heated cantilever. In this bottom image, brighter regions have higher resonant frequencies corresponding to stiffer regions in the sample. Note the correspondence between the brighter round regions in the top AFM image (the filler particles) and the bright regions in the contact resonance map.

FIG. 11 shows a profile of the contact resonance and the glass transition temperatures in the vicinity of a filler particle. The top image shows an AFM topography image of a highly filled epoxy indicating where contact resonance and glass transition temperature measurements were made. The plot below shows spatially resolved measurements of glass transition

temperature and contact resonance on top of and adjacent to a filler particle. This measurement shows the spatial distribution of the changes in stiffness and thermal properties of the epoxy due to the inclusion of filler particles.

FIG. 12 shows a simplified flow diagram of a method for measuring viscoelastic properties of materials as a function of temperature and frequency using a self-heated cantilever probe. It also illustrates the ability to create spatially resolved maps (1228) of viscoelastic properties at multiple locations on a sample surface. In this embodiment, the process starts by moving the probe tip to a desired XY position on the sample (step 1200). This can be achieved by moving the probe, the sample or a combination of both. The motion can be generated any number of ways including the use one or more motorized translation stages, piezoelectric scanners or any other device that produces relative motion between the cantilever probe and the sample. In the next step (1202), the probe is ramped to a desired temperature T_i to heat a microscopic region of the sample. The use of self-heatable cantilevers has a dramatic advantage over conventional DMA and/or variable temperature AFM. The small heater area (on the order of 10 $\mu\text{m} \times 5 \mu\text{m}$) and a very small contact area between the probe tip and sample (~10 nm contact radius) lead to a very small heated volume of at most a few μm^3 . This means the heated region can equilibrate extremely quickly, allowing temperature ramp rates as high as 600,000° C/min. After the temperature adjustment, the system performs a measurement (1204) and correction (1206) of the static force applied between the tip and sample. This can be a critical step because as the probe temperature is rapidly ramped, the tip-sample force can change due to thermal expansion of the sample and thermal stress bending of the cantilever. As such, the normal force feedback loop employed in AFM can fail to maintain a constant interaction force as the temperature changes. This can be a critical issue for measurements of glass contact resonance frequencies and glass transitions because the contact resonant frequency depends critically on the surface contact stiffness which in turn depends on the tip-sample contact force. To maintain a constant interaction force this process next performs a rapid tip withdrawal and re-engagement to determine the adhesion and point of contact (1204). From this, the system can reset the static tip-sample force to a desired value (1206). This can be accomplished by moving the tip, the sample or a combination of both. It can also be accomplished by adjusting the DC level of the Lorentz force applied to the cantilever. This can have speed advantages since the static force can be ramped and controlled very quickly without exciting mechanical resonances in other portions of the AFM. Next the Lorentz force is modulated over a range of frequencies ω_i (1208) while measuring the cantilever response (1210). Using the known loading force from steps 1204-1206 and the dynamic force (1208), and cantilever response (1210), it is possible to calculate viscoelastic properties of the sample, including storage modulus, loss modulus, and/or $\tan \delta$. These properties can be measured as a function of a plurality of applied frequencies ω_i (1212 and 1224), sample temperatures T_i (1214 and 1226), and/or sample locations (1216 and 1228). Spatially resolved maps can be created of any desired property including cantilever amplitude, phase, storage modulus (E'), loss modulus (E''), loss tangent ($\tan \delta$), glass transition (T_g), melting temperature (T_m) and other related properties. For quantitative measurements, it can be desirable to use knowledge of the tip shape and/or measurements on a known reference sample (1218). Note that it is not required that the temperature and frequency sweep loops operate synchronously. For example it is possible to ramp the probe tip temperature continuously and

asynchronously measure the frequency dependent cantilever response as the temperature is changing. The only practical issue is that the temperature ramp rate is slow enough that that it is not changing dramatically during a single frequency sweep. But in the case of 10 msec frequency sweeps, a temperature ramp rate of 100° C./sec would result in only a 1° C. change during the sweep.

The entire sample or a portion of the sample may also be heated or cooled by a more macroscopic heater/cooler stage. (This can be especially desirable for studying samples with glass transition temperatures below room temperature.)

FIG. 13 shows a measurement of the wideband viscoelastic response on a sample of highly crystalline polyethylene terephthalate (PET). Highly crystalline polymers are problematic for conventional nanothermal analysis because the crystalline domains (that don't undergo a glass transition) can support the tip and prevent penetration even when amorphous regions go through a glass transition. FIG. 13 shows variable temperature measurement of viscoelastic response on polyethylene terephthalate (PET) showing amplitude (A) and phase (B). For this measurement, the cantilever response was measured from 20 kHz to 200 kHz while ramping the temperature between 40 and 300° C. The phase plot (B) clearly shows peaks at both the glass transition and the melt.

Rapid measurement speeds. For the example shown in FIG. 13, the frequency sweeps were obtained in 10 msec. Each frequency sweep was interleaved with a measurement and adjustment of static tip-sample force, also accomplished in 10 msec. The temperature was asynchronously ramped at 10° C./sec. Thus the entire measurement was performed in roughly 26 seconds. While this temperature ramp rate was selected to correspond closer to temperature ramp rates used in bulk analysis, much faster measurements are possible. The probes can be ramped at up to 10,000° C./sec or more, so this entire temperature ramp could have been performed in 26 msec or less. Therefore the practical limit is set only by the temperature and frequency resolution desired. For example, if one wanted measurements at every 5° C. between 40 and 300° C. (53 total temperature steps), with interleaved force control and frequency sweep steps at 10 msec duration, the entire measurement can be accomplished in $53 \times (10 \text{ msec} + 10 \text{ msec}) = 1060 \text{ msec}$, or around 1 second. This is in distinct contrast to conventional DMA and variable temperature AFM that is typically performed at around 1-10° C./minute. For measurements at every 5° C. it would require 30-300 seconds for each ramp. So for a ramp between 40 and 300° C., with 5° C. temperature resolution (53 steps) would require 1590-15900 seconds (0.4-4 hours) for ramping plus the measurement time. In practice DMA users often wait 30-45 minutes for the system to stabilize at each temperature such that it can take hours, days or a week or more to characterize a polymer over a broad range of temperature and frequencies. In addition, conventional DMAs cannot measure samples at frequencies above around 100 Hz (or 1-2 kHz in a rare high end instrument), so most DMAs cannot access anything close to the frequency range enabled by current invention. In practice, embodiments of the current invention can provide this information at nanoscale spatial resolution and ~1000x faster and ~1000x higher frequencies than conventional instruments.

Time Temperature Superposition. FIG. 14 shows the process of time-temperature superposition (TTS) to create a "master curve" that extrapolates the viscoelastic response of a material over a broad range of frequencies. Time-temperature superposition is a technique that is used to predict material behavior outside the frequency range available to the instrument and to make estimates of material energies. TTS makes use of the fact that the frequency dependent elastic

response of some materials has a similar shape at adjacent temperatures. Specifically, the frequency dependent response at one temperature is shifted to be most similar to the response at a reference temperature. In the simplest case, this is accomplished by scaling the frequency axis for measurements at different temperatures to get the best correlation to the reference temperature. There are two key results from this process (1) "the master curve" and (2) energies. The master curve integrates measurements over a range of temperatures to predict a viscoelastic response of a material, often over many decades of frequency. FIG. 14A shows a series of measurements of cantilever indentation versus frequency for a constant force at a series of different temperatures. FIG. 14B shows the application of time-temperature superposition where the frequency axis of each curve is scaled to be most similar to the curves at adjacent temperatures. FIG. 14C shows an example "master curve" indicating average indentation as a function of frequency taking contributions from each temperature and the time-temperature superposition scaling. This indentation curve can be transformed into a plot of elastic modulus using an appropriate contact mechanics model. By measuring indentation amplitude and phase (or equivalently the indentation components that are in phase and quadrature with the Lorentz force actuation), it is possible to measure the storage and loss modulus, E' and E". The ratio E"/E' is defined as the loss tangent, or tan δ.

Master curves that plot these properties as a function of temperature and/or frequency can provide crucial information about polymer systems. The low frequency/terminal behavior provides information about flow behavior of the material whereas the higher frequencies provide us with material properties such as Tg, glassy and rubbery plateau moduli. The master curve can be used to predict molecular weight distribution, start up of flow and strain hardening for a polymer using theoretical models. Such measurements are also invaluable to the fundamental research on polymer relaxation not only in terms of verifying the model predictions but also improving the models. A comprehensive master curve is regarded as a material imprint that can be used to estimate a material's behavior for a range of application temperatures and durations. In embodiments, the current invention provides a method to extract this information at time scales much shorter than conventional instruments and over much higher frequency ranges.

Activation energy. From the shift factors used in time temperature superposition, one can extract the energies of the sample. FIG. 15 shows a plot of the log of the shift factors versus reciprocal temperature (1/T). In the case of Arrhenius behavior, the slope of the log(shift factor) vs 1/T is related to the energy. As such it is possible to use the heatable AFM cantilever probes to measure the energy of microscopic regions of a sample in very short times.

Concentration of Lorentz force near tip. In embodiments, the current invention has significant advantages versus prior commercial implementation of Lorentz force actuation. A benefit of certain embodiments is that the force is applied very near the end of the cantilever, as discussed previously. This results from the fact that the self-heated cantilevers used in embodiments of the invention preferably have parallel cantilever arms, as shown in FIGS. 1 and 16A. For any arbitrary orientation of the magnetic field, the net Lorentz flexural force on the two arms is in opposite directions and substantially cancel each other. The dominant vertical force is then from Lorentz force on the current segment near the AFM tip. (Note that the magnetic field vectors shown in FIG. 16 are intended to indicate an arbitrary field direction, and not intended to imply a preferred direction of the magnetic field.)

A Lorentz force actuation scheme was previously developed using V-shaped cantilevers for oscillating them in liquid. The inventors are not aware that this technique has been used for measuring mechanical properties of materials, but even in this case the technique would still have significant disadvantages if one were to use it to attempt to measure an indentation into a sample in response to the Lorentz force. Two reasons include that (1) the Lorentz force would be applied over the entire length of the cantilever; and (2) the cantilevers used are very low spring constant and low resonance frequency, thus limiting the force and bandwidth that could be used; and (3) the cantilever deflection signals would be very similar for both hard and soft samples.

The first issue is illustrated in FIG. 16B. In the case of a V-shaped cantilever (FIG. 16B), the two currents I_1 and I_2 take diagonal paths. While the Lorentz force components of the current in the Y-direction can cancel each other, there is a net force along the entire length of the cantilever from the current component in the X direction. This distributed force creates disadvantages for mapping mechanical properties of materials, as illustrated in FIG. 17 and discussed below. The issue with the prior art is outlined in FIG. 17. Illustrated on the left column (FIGS. 17A-C) is the case where Lorentz force is distributed along the length of the cantilever. Two cases are shown in this column, one where the force is applied on a hard material (FIG. 17A) and one on a softer sample (FIG. 17B). A simplified point-mass model is shown in FIG. 17C. In both cases the softer spring is the cantilever as indicated by stiffness k_c . So the vast majority of the applied Lorentz force would go into deflection of the cantilever rather than the indentation of the sample. So both in the case of the hard material and the soft material the cantilever deflections δ_H and δ_s are very similar. The indentation into the sample h would be the very small difference between δ_H and δ_s . Thus any attempt to measure the indentation h would require pulling out a small differential indentation from a large cantilever deflection background.

The “i-drive” system commercialized by Asylum supports two different cantilever spring constants, 0.02 and 0.09 N/m. Within the range of cantilevers used by practitioners of AFM, these cantilever spring constants are known to be “soft.” By contrast, the contact stiffness of even a common polymer with an reduced elastic modulus of around 3 GPa would give a surface contact stiffness of around 50 N/m if indented with a 20 nm tip radius using the Hertzian approximation. So the cantilever spring constant is around 500-2500 less than the spring constant of common polymer surface. So if one were attempt to use an “i-drive” type scheme to apply a Lorentz force to indent a polymer surface, the vast majority of the cantilever deflection would be the result of bending the soft spring of the i-drive cantilever, not indentation of the sample. Furthermore, the sample indentation would be of orders of magnitude smaller than the bend of the cantilever. The magnitude of the cantilever bend on a 3 GPa polymer would be very similar to the bend on an infinitely rigid sample.

Now, this situation is compared to embodiments of the current invention. In the embodiments of the current invention, the Lorentz force is applied very close to the tip end of the cantilever as shown in FIGS. 17D-E. In this case a very small deflection and indentation is detected on a hard surface (FIG. 17D), where $\delta_H \approx h \approx 0$. When the Lorentz force F_L is applied on a soft sample (FIG. 2E), by comparison, the indentation h can be measured directly without differential measurement since $h \approx \delta_H$. That is the indentation h is directly proportional to a signal indicative of the cantilever deflection. So measuring the cantilever deflection gives a direct measurement of the indentation of the probe tip into the sample.

There are other advantages to apply the force at the tip end of the cantilever. As shown in FIGS. 17C and 17F the cantilever and sample can be considered (crudely) as a coupled spring/dashpot system. In the case of a distributed force, the cantilever acts essentially like a shock absorber that can attenuate the Lorentz force before it reaches the sample. Above the first resonance of the cantilever, the transmitted force will be substantially attenuated by the transfer function of the cantilever. By comparison, when the force is applied to the end of the cantilever near the tip, the motion of the cantilever primarily results from indentation of the sample. Thus the motion of the end of the cantilever is a more direct measurement of the strain resulting from the applied force. This is also an advantage versus conventional AFM force curve measurements where one must perform a differential measurement comparing the deflection on an unknown sample to a measurement on a sample assumed to be rigid. The indentation on the unknown sample is the difference between the cantilever deflections on the unknown sample vs. the rigid sample. This differential measurement, while very commonly used, still involves detecting a potentially small indentation against a large cantilever deflection background.

High speed force control and imaging. This section discusses the ability to use Lorentz force actuation under embodiments of the current invention for high speed force control and AFM imaging. In recent years, AFM instruments have been commercialized using pulsed force techniques, where the tip is oscillated sinusoidally by a z-actuator at a frequency much lower than the contact resonance to bring the tip in and out of contact with the sample. During the sinusoidal oscillations, the cantilever deflection is measured and versus the position of the z-actuator. For example, products have been commercialized by Witec (Pulsed Force Mode) and Bruker (“PeakForce Tapping”). In these techniques, typically the system converts the measured deflection and z motion into an AFM force curve. From the force curve, one can measure the contact point, stiffness, adhesion, and energy dissipation, for example, as described in U.S. Pat. Nos. 6,880,386 and 7,129,486, and U.S. Patent Application Publication No. 2011/0167524. By repeating this measurement at many locations on a sample one can create an image of the surface topography or other properties of the sample. This technique has been very successful, but is limited in its speed of operation. Typically, the cantilever is moved in and out of contact with a large range piezoelectric actuator, for example an actuator capable of moving the tip or sample by many microns. The stiffness of this actuator and its moving mass can limit the maximum speed at which the pulsed force oscillation can operate.

Embodiments of the current invention have distinct advantages over the prior art. First, since the Lorentz force is applied very near the tip, the system can very efficiently control the tip motion without undue delays or attenuation due to the problem of applying the force on the other side of a soft cantilever spring. Second, the sign of the Lorentz force can be controlled by the direction of the current. So the Lorentz force can apply an attractive or a repulsive force to the AFM tip. Next, the Lorentz force actuation scheme of the current invention has no moving parts except the cantilever itself and thus does not suffer from parasitic resonances that can be excited by moving larger piezoelectric z-actuators. Employing the wide bandwidth of the Lorentz force, the cantilever can be actuated into and away from the surface at frequencies much higher than by large range piezoelectric actuators, including frequencies >100 kHz and >1 MHz.

It is also worthwhile to compare this to conventional tapping mode AFM. In tapping mode AFM, the cantilever is

oscillated at resonance. Stiff cantilevers (often >3 N/m and usually ~ 40 N/m) are normally used for tapping such that the restoring force of the cantilever is sufficient to pull the tip off the surface on each oscillation cycle. For pulsed force mode operation, by contrast, soft cantilevers are usually used, mostly <1 N/m. The z-actuator is responsible for having sufficient range to overcome the adhesion and pull the tip off the surface. The current invention, however, can achieve the best of both worlds. Soft spring constant cantilevers can be used if desired to apply minimal force, and it is not necessary to rely on the cantilever's restoring force or a large actuator to pull the tip off the surface. Instead, embodiments of the current invention can use the large available Lorentz force to overcome attractive forces and pull the tip off the surface. In this way pulsed force imaging can be realized with oscillation frequencies much higher than the prior art.

It is also possible to use Lorentz force and, if desired, in combination with thermomechanical bending to perform quasistatic indentation experiments like those employed in nanoindenters. In this case the DC current through the cantilever can be ramped up and down to increase and decrease the loading force on the sample. Since the force is applied near the tip, the indentation can be read out directly by measuring the deflection of the cantilever. The inventors have demonstrated generating indentation forces in excess of 1000 nN with Lorentz force actuation with currents.

High Speed force control interleaved with variable frequency Measurements. FIG. 18 shows an embodiment of the current invention employed to perform rapid measurements of the cantilever response as a function of frequency, and if desired, as a function of temperature. Three signals are shown in this figure. The top trace (1802) shows a signal used to adjust the average position of the cantilever relative to the sample. In one embodiment this signal drive can be a piezo-electric actuator that moves the cantilever or sample. It can alternately drive the DC current in the cantilever, employing the thermomechanical bending and/or Lorentz force to bring the tip in and out of contact with the sample. In the top trace, we identify three subsets of the waveform. The segment 1804 is the approach ramp, used to approach the tip towards the sample surface, while the segment 1808, the retract ramp, is used to pull the tip back off the surface. The shape of these segments may take many forms. They may be a linear ramp, a portion of a sine wave, trapezoidal profile, or any of a number of sigmoidal functions. The approach and retract ramp also need not be symmetric. Note, specifically, that in embodiments of the current invention there is no need for the approach and retract curves to be consistent sinusoidal oscillations as employed in the prior art. In a preferred embodiment the slopes at the beginning and end of the approach ramp are near zero. In the case of an actuator, this reduces the acceleration impulse that can excite unwanted resonances. The cantilever is then held at a constant average position during optional hold period 1806. During this period, an AC actuation 1810 may be applied to the cantilever via the Lorentz force. The AC actuation may comprise a single frequency oscillation, a series of successive single frequency oscillations over a plurality of frequencies, a chirp waveform (swept frequency sine wave), a pulse, a noise burst or other arbitrary waveform intended to excite the dynamic response of the cantilever and sample. During both the approach ramp, hold period and retract ramp, the cantilever deflection (1814) may be monitored. The cantilever deflection signal (1814) can be analyzed for several quantities. First, point 1816 indicates the point of contact between the tip and sample. Point 1826 indicates the point of maximum static deflection. Region 1818 can be used to determine the dynamic response

of the cantilever, for example to determine the frequency of a contact resonance (1820) or more generally the frequency dependent indentation of the sample. As mentioned previously, measuring the indentation of the sample as a function of frequency can be used to determine viscoelastic properties like storage modulus, loss modulus, and $\tan \delta$. At the completion of the AC actuation 1812, the cantilever is retracted from the surface with retract ramp 1808. During the process the cantilever tip may experience some adhesion with the sample. Rupture of adhesion at point 1822 can cause free resonance oscillation (1824) of the cantilever. The maximum quasistatic force can be obtained by determining the difference between the cantilever deflection at the point of maximum deflection and from the point of contact (1816), or in the case of significant adhesion, the point of separation (1822). A feedback loop can then adjust the center or maximum point of the subsequent approach ramps 1804 to maintain a desired value of quasistatic tip-sample force.

An alternate embodiment is shown in FIG. 19. In this case 20 a slower force curve is interleaved with a swept frequency AC actuation. This type of arrangement may be preferable when one wants to obtain more data point of the cantilever deflection during the approach and/or withdraw ramp, for example to extract quasistatic or low frequency viscoelastic behavior. 25 At left in FIG. 19 there is a series of schematic frames of the measurement comprising a quasistatic force measurement followed by a swept frequency chirp. The frame numbers 1-5 correspond to points identified in the traces at right. The top trace (1902) corresponds again to the signal used to control the average position of the cantilever, for example a piezo electric actuator. The control signal has two main sequences, the approach-retract sequence (1904) and the ramp and hold sequence (1906). The middle trace (1908) shows the variable frequency AC excitation (1910) that is applied during the 30 ramp and hold period (1906). The bottom trace shows the cantilever deflection during the application of the z-actuator control voltage and AC actuation. The first segment (1914) corresponds to the approach retract sequence (1904) and the second sequence (1916) shows the cantilever response to the 35 AC excitation.

FIG. 20 shows the same cantilever response from FIG. 19, but with some features that can be observed from the measurement. As with the description of FIG. 19, it is possible to determine to static load from the maximum deflection at point 45 2003 or 2006 versus the baseline/contact point (2001). As before, a feedback loop may be used to adjust the s-actuator control signal to maintain a desired level of contact force. In addition, one can determine the adhesion from the difference 50 between maximum negative deflection and the baseline, as is performed in traditional AFM force curve measurements. The quasistatic elasticity can be determined from the approach (2002) and/or retract (2005) curves using traditional AFM force curve analysis. In addition, with the use of self-heated probes, it is possible to perform a local measure of thermal 55 expansion of the heated region of the sample. The thermal expansion can be obtained by the difference between the peak deflection at the end of the hold period (2009) versus the beginning (2006). Depending on the frequency range selected, the chirp response can be analyzed to determine 60 wideband dynamic stiffness (2010) and/or the contact resonant frequencies (2012).

Force control during temperature ramps. The process of measuring and maintaining a consistent tip-sample force through repeated approach-retract cycles can be especially important during the high speed temperature ramps used in one embodiment of the current invention. In conventional nanothermal analysis, this force is not well controlled. As the 65

tip-sample temperature is ramped in conventional nanothermal analysis, both sample thermal expansion and bimetallic bending of the AFM cantilever conspire to alter the tip-sample force. While force control is a standard part of conventional AFM, the most commonly used AFM force feedback loop fails to maintain a constant force under dramatic temperature changes. The reason is that standard AFM feedback loops for contact mode maintain a constant deflection of the cantilever. In the case of rapid temperature ramps, the bimetallic bending of the cantilever creates a force error that is not corrected by the standard feedback loop. Further, once a material reaches a softening temperature, the feedback loop fails completely, driving the tip further into the surface in its attempt to maintain a constant deflection. In embodiments under the current invention, the tip repeatedly approaches and withdraws from the sample during the temperature ramp, each time correcting for any thermal expansion and or thermal stress bending. FIG. 19 compares the force during a conventional nanoTA temperature ramp with one obtained under the current invention. In this example, the temperature was ramped over 100° C. in a few seconds. During this ramp conventional nanoTA (trace 2101) can induce an 8× change in tip-sample force, while the current invention (trace 2102) maintains a consistent force. This consistent tip-sample force is extremely beneficial for accurate measurements of temperature dependent elasticity, especially using contact resonance measurements where the resonant frequency would otherwise shift with uncontrolled load.

Alternate Embodiments

Embodiments of the current invention have been described to include self-heatable cantilevers, Lorentz force actuation to measure properties of a sample as a function of temperature, frequency, and/or position on a sample. Substantial benefit can be also obtained by using a subset of these capabilities. For example, it is possible to use non-heating cantilevers but still employ Lorentz force actuation to measure the contact resonance of a sample and/or the wideband dynamic response of a sample. In this case the temperature can be fixed, or the sample temperature can be adjusted using conventional heater/cooler modules used in DMA and AFM. In this case, there is still substantial benefit of the parallel cantilever arm arrangement to provide the majority of the force on the cantilever near the tip end of the cantilever.

Additionally, it is possible to use a self-heating cantilever without the Lorentz force actuation. In this case, other actuation mechanisms can be used to excite the cantilever oscillation. These can include external piezoelectric and/or ultrasonic actuators that modulate the cantilever base and/or the sample. It can also include electrostatic, thermomechanical, and piezoelectric actuation of the cantilever arms. In this embodiment, the rapid temperature ramping benefits of the current invention may still be maintained.

In another embodiment it is possible to arrange separate conduction paths for the heater and the Lorentz drive. In this case, it can be possible to drive large currents through the cantilever probe arms and ends without necessarily generating large dissipation in the heater. The inventors have recently developed three leg thermal probes incorporating a diode. An arrangement with a diode can be used to control whether or not current passes primarily through a high conduction path or the highly resistive path (the heater).

The heaters in the current commercially available probes are 12 μm×6 μm. This size can be adjusted to increase the Lorentz force. For the optimal orientation of the magnetic field, the Lorentz force is substantially proportional to the

length of the conducting path perpendicular to the field. Thus fabrication of a probe with a longer heater element will increase the Lorentz force. For example 24×6 μm would double the Lorentz force. It is also possible to arrange the end 5 region of the cantilever to be partially highly conductive and partially highly resistive. For example it is possible to maintain a heater of 12 μm×6 μm while extending the end region of the cantilever with a highly conductive path. This would largely maintain the mechanical properties of the cantilever, 10 while increasing the Lorentz force.

It will be apparent to the skilled artisan that there are numerous changes that may be made in embodiments described herein without departing from the spirit and scope of the invention. Other features not mentioned in the specification, 15 but known to one skilled in the art may be integrated as well without departing from the spirit and scope of the present invention. There are, for example, a wide array of materials, apparatuses, and methods which may be interchangeably used, and there are many changes that may be made in dimensions 20 and so forth to accommodate different needs which may be used, all within the scope of the invention.

The invention may be further understood by the following non-limiting examples.

EXAMPLE 1

Lorentz Force Actuation of a Heated Atomic Force Microscope Cantilever

The atomic force microscope (AFM) enables nanomechanical measurements with high spatial resolution. Some AFM imaging modes require the cantilever tip to oscillate in contact with or near the surface. The cantilever oscillation can be actuated with piezoelectric, electrostatic, photothermal, 30 thermo mechanical and magnetic schemes. The integration of cantilever actuation with other cantilever functions, such as integrated heating, has not been fully explored. This example presents magnetic actuation of a self-heating cantilever.

Magnetic actuation induced by Lorentz force is relatively 40 less considered as an actuation mechanism, but it is also easy to implement to a cantilever by defining current path through the cantilever and place it in the external magnetic field. It does not have upper limit in actuation frequency, and enables individual control of temperature and deflection on cantilever 45 at the same time. However, only a few published papers have dealt with Lorentz force actuation, and there is no consideration about magnetic field direction and thermomechanical crosstalk.

This example reports Lorentz force induced actuation on 50 silicon microcantilevers considering the magnetic field direction and crosstalk with thermomechanical actuation. And using the actuation scheme, individual heating and actuation control is demonstrated by measuring material softening temperature of polymer.

Theory and Instrumentation. FIG. (22a) shows a schematic of the cantilever actuated by Lorentz force. An oscillating current passes through cantilever, and the cantilever is held close to a permanent magnet. The Lorentz force exerted on the cantilever is governed by the current through the cantilever and the external magnetic field

$$F(B)=I(I \times B), \quad (1)$$

where I is the length of current passage, I is the current vector, and B is the magnetic field vector. The current flowing 65 through the cantilever changes directions as it follows the cantilever shape. The Lorentz force acting on each section is accounted for separately and then added together to obtain the

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net force exerted on the whole cantilever. The Lorentz force is equal and opposite on the two cantilever legs, and can be neglected. Therefore, the net force acting on the cantilever is governed by only I_y , yielding

$$F(B) = 2I\sin\phi(B_z\hat{x} + B_x\hat{z}), \quad (2)$$

where \hat{x} and \hat{z} are directional unit vectors, and $2I\sin\phi$ denotes the distance between the two legs ($31\text{ }\mu\text{m}$). The force acting perpendicular to the cantilever, which is responsible for the cantilever deflection, is

$$F_{\perp}(B) = 2I\sin\phi(B_z\sin\theta - B_x\cos\theta). \quad (3)$$

Since the cantilever tilt angle θ is usually quite small, 11° for this experiment, the cantilever deflection is dominated by B_x rather than B_z . That is, the Lorentz force from the parallel magnetic field to the cantilever is larger than the Lorentz force from the perpendicular field.

A magnetic dipole m generated by the closed current loop may also induce the force by interacting with magnetic field gradient as

$$F(\nabla B) = \nabla(m \cdot B) = \nabla(\tau S \cdot B), \quad (4)$$

where S is the area vector pointing normal to the area surrounded by the current loop. Because the m is dominated by the triangular region of the cantilever where the magnetic field is highly concentrated, therefore, the S should be the area surrounded by the triangular region. Then the force perpendicular to the cantilever due to this magnetic field gradient is approximated as

$$F_k(\nabla B) \approx I^2\sin\phi\cos\phi\left(\frac{dB_z}{dz} + \frac{dB_x}{dz}\right). \quad (5)$$

However, although the field gradient is quite larger than the field itself near the magnet surface, the force of Eq. (5) is at least two orders of magnitude smaller than that of Eq. (3) owing to the very small I^2 term. The force acting on the cantilever is dominated by the magnetic field, and not by the magnetic field gradient.

FIG. 22(b) shows a scanning electron microscope (SEM) micrograph of the doped silicon micro-cantilever used in the experiment. This type of self-heated cantilever was originally designed for data storage, but has also been used for thermal-imaging, nanolithography and nano thermal analysis. The unique nature of the current loop enables the Lorentz force actuation described in this example. The cantilever used in the experiment was $170\text{ }\mu\text{m}$ long and $1\text{ }\mu\text{m}$ thick, and its resonance frequency and spring constant was 65.4 kHz and 0.55 N/m . The cantilever was mounted in an MFP-3D AFM (Asylum Research) and powered by a function generator while placed near a NdFeB cube magnet. Since the Lorentz force is governed not by voltage but by current, the cantilever was operated in series with an external resistor having much higher resistance ($47\text{ k}\Omega$) than the cantilever ($1.9\text{ k}\Omega$) to keep the total resistance of the circuit to be constant, making the pure harmonic voltage source close to the pure harmonic current source.

Current flow through the cantilever induces a Lorentz force as well as a resistive heating within the cantilever. The temperature rise associated with the resistive heating induces thermomechanical deflections. An AC current having angular frequency ω results in Lorentz deflection oscillating at ω , and also generates temperature oscillation in the cantilever at 2ω , leading to thermomechanical deflection also at 2ω . The cantilever deflection signal from the AFM was measured using an

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SR 850 lock-in amplifier (Stanford Research Systems) to investigate both Lorentz (1ω) and thermomechanical (2ω) deflections.

Since the thermomechanical deflection was linearly proportional to the temperature rise, the static and oscillating temperature were measured using Raman spectroscopy and 3ω method, respectively.

To compare the experimental result to theory, the Lorentz force under this circumstance was calculated from the magnetic field around the magnet. The 3D magnetic field and the gradient around the cube magnet were calculated by using COMSOL. Then the Lorentz force acting on the cantilever near the magnet was calculated from the magnetic field and the current applied to the cantilever, using Eqs. (3) and (5). Because the calculation evaluates force, whereas the measurement yields deflection, the cantilever deflection was converted into force with the spring constant of the cantilever ($k=0.55\text{ N/m}$). The magnet strength was the only unknown, and it was used as the fitting parameter.

Experiments and Results. A. Deflection spectra versus power and frequency. FIGS. 2(a) and 2(b) show the deflection amplitude of the cantilever with 1 mA sinusoidal current $I \sin[2\pi(f_0/n)t]$, where $f_0=\omega_0/2\pi$ is the cantilever fundamental resonance frequency. At low frequency below the thermal time constant of the cantilever, both the thermomechanical and Lorentz deflection are nearly constant, and correspond to the static deflection. The static thermomechanical deflection is two times larger than the deflection amplitude at low frequency shown in FIG. 2(a), because the thermomechanical deflection always occurs in one direction regardless of the current direction, making the deflection amplitude to be half of the maximum deflection. In this static regime, the thermomechanical deflection is higher than the Lorentz deflection. As the frequency increases, the cantilever deflection by Lorentz force does not show a distinct dependency on the frequency, however, the thermo-mechanical deflection decreases significantly when the actuation frequency exceeds the cantilever thermal time constant which is on the order of $100\text{ }\mu\text{s}$. The Q factor of the silicon cantilever was about 66, and so the discrepancy between the Lorentz and thermomechanical deflections becomes further severe at the resonance frequency, making the Lorentz deflection 1000 times higher than thermo mechanical deflection. The thermomechanical deflection is relatively small because the cantilever is made of only single crystal silicon which induces little bimaterial deflection, and the heater located at the cantilever end does not uniformly heat the entire cantilever. Hence, the cantilever actuation near the resonance is purely induced by Lorentz force. The deflection amplitude by Lorentz force reaches to 336 nm at the resonance, sufficiently high not only for the applications detecting resonance shift such as mass sensing but also for general tapping-mode imaging.

The usefulness of the actuation scheme is validated by imaging a calibration grating with Lorentz actuation. The grating, having 100 nm trenches, was placed on the magnet, and the cantilever was powered with the internal function generator of the AFM. This AFM function generator, called DDS, originally supplies voltage to the piezoactuating oscillator on the cantilever holder, implementing the feedback loop of the AFM fully with the Lorentz actuation. FIG. 4 is the tapping-mode image acquired from this experiment, which shows no difference compared to the normal piezo-driven imaging.

As the Lorentz and thermomechanical deflection are governed by current and temperature, the two deflection mechanisms on the current and temperature are related to examine the crosstalk between them. The static and oscillating tem-

perature, as stated previously, were measured by Raman spectroscopy and 300 method, respectively. It should be noted that all the temperatures here are the heater temperature at the cantilever end, implying a temperature much smaller than the measurement is actually responsible for the thermomechanical deflection. However, the thermally linear system ensures the cantilever temperature linearly corresponds to the heater temperature, enabling valid physical interpretation.

FIG. 3(c) shows the amplitude of the temperature oscillation and the thermomechanical deflection as a function of the cantilever current frequency. FIG. 3(b) shows the static temperature rise and the temperature amplitude of oscillation at resonance, which are responsible for the static deflection and deflection amplitude at resonance. The temperature amplitude at resonance is only 3.5 K, resulting in a relatively small deflection. However, the huge static temperature rise (172 K) induces a large static thermomechanical deflection.

FIGS. 24 and 3(a) show the static and oscillating cantilever behavior as a function of the temperature and applied current. The static thermomechanical deflection is linear with the temperature rise, and the Lorentz deflection also shows good linearity to the current, both in steady-state and at resonance, as expected by principle. Since the thermomechanical deflection decreases as fast as the frequency increases, it (0.32 nm) is far smaller than the Lorentz deflection (10.5 nm) even at thermomechanical resonance ($f_0/2 = 32.7$ kHz). Therefore the thermomechanical deflection shown in FIG. 3(a) is not purely thermomechanical, but contains harmonic artifacts of Lorentz deflection. However, it still shows quadratic relations to the current, meaning that the Lorentz deflection is quite close to pure harmonic oscillation.

B. Influence of field direction on Lorentz force. The direction of the magnetic field is critical for Lorentz actuation. Here, the effect of the magnetic field direction on the Lorentz force is investigated by changing the cantilever location relative to the magnet, and also by changing the magnet orientation. The cantilever was placed 200 μm above the 3 mm cube magnet and powered by 0.2 mA sinusoidal current. The cantilever deflection was measured as a function of lateral position, resulting in a 2D map of cantilever deflection amplitude with 100 μm spatial resolution. FIGS. 5a-5c shows the 2D deflection maps above a cube magnet for different magnet orientations (O1, O2, O3). The experiment was also performed above a circular disk magnet (O4). For the magnetic orientation of O1 and O4, the vertically aligned pole, the maximum deflection can be achieved along the edge of the magnet where the B_x is maximized, and there's a zero deflection region, implying the forces by B_x and B_z are canceled out. FIG. 5(d) shows the maximum deflection line along the magnet edge. For O2, the magnetic pole aligned parallel to the cantilever, the deflection amplitude is quite uniform except the edge of the magnet since B_z is the dominant magnetic field direction with this magnet orientation. Other experiments were performed with this orientation because the almost constant deflection amplitude, regardless of the cantilever position, facilitates easy experimentation, especially in imaging. Eq. (3) means that B_y does not induce the cantilever deflection, therefore, there's no deflection along the center line ($y=0$) on the magnet with magnetic orientation of O3, where the only existing magnetic field is B_y .

FIG. 6(a) shows the calculated magnetic field around the cube magnet with vertical pole (O1), on the xz plane ($y=0$). FIG. 6(b) shows the calculation and measurement of the Lorentz force with vertical and horizontal magnetic field (O1, O2), which compare very well. The Lorentz force with the O3 magnet orientation is zero in both calculation and measurement. The field strengths of the magnet used to fit the experi-

ment and calculation are different for each magnet orientation, 0.41 T for O1 and 0.26 T for O2.

FIG. 7 shows the portion of the force induced by each magnetic field direction, giving a clear insight about the dependence of Lorentz force on the magnetic field direction and magnet orientation. As predicted from Equations (3) and (5), B_x dominates the Lorentz force acting on the cantilever and the force induced by the magnetic field gradient is indistinguishably small and is not plotted on the figure.

C. Detecting material softening by Lorentz nanoTA. As one application of Lorentz force actuation, nanoTA (nanoscale thermal analysis) was performed to sense the glass transition temperature T_g of a polymer by looking at the shift of contact resonance frequency. The conventional nanoTA works by detecting a slight penetration of the tip into the sample at T_g , while increasing the tip temperature. The problem of the method is that, the T_g for highly filled and highly cross-linked materials are not easy to detect because the softening at T_g is insufficient and the thermal expansion is quite large near the T_g , counteracting the softening. However, by sensing the resonance frequency shift, the measurement becomes free from this problem.

The measurement was done on four randomly selected regions of a nonconducting underfill epoxy (CHIPCOAT U8437-2, NAMICS Corporation). This is a highly filled epoxy (2-10 μm silica particles) that improves the mechanical and thermal performance of the material, making it hard to use conventional nanoTA method. A small printed circuit board with a sample of the epoxy was placed on a 12.7 mm×1 mm thick NdFeB disk magnet such that the region of interest on the sample was at the outer diameter of the magnet, where the Lorentz deflection was maximum. A self-heating AFM cantilever (AN200, Anasys Instruments) was periodically approached to the surface to determine the point of contact with the sample. After each tip approach, the cantilever was moved to a selected loading force and then a chirp waveform ($2V_{pp}$ AC) was applied across the legs of the cantilever. A DC voltage was applied across the heater to ramp the probe temperature from just over ambient to above the glass transition temperature. Approach curves were repeated during this process to ensure a constant loading force even as the temperature was ramped.

FIG. 8 shows the contact resonance frequency versus the temperature at the tip, indicating the peak of the resonance frequency corresponding to the T_g . The T_g specified by the manufacturer (137°C.) is in good agreement with the average T_g observed in the measurements, however, the contact resonance nanoTA measurements show local variations not observable in bulk T_g measurements. This shows that the method can resolve the local T_g change, allowing for extraction of the information of local composition difference.

The Lorentz drive system described in the current application can further be used with a magnet that is installed directly in the AFM measurement head, as shown schematically in FIG. 25. The inventors have used a NeFeB magnet (2501) with a high permeability magnetic pole piece (2503) to focus the field in the vicinity of the AFM tip (2505). The NeFeB magnet fits into a slot in a magnetic stainless steel cover on the bottom of the AFM head (not shown). The mounting slot allows the magnet to be slid towards the AFM tip for highest magnetic force and away from the AFM tip (motion indicated by the arrow) to provide sufficient clearance to change the tip without risking damage to the tip. The self-heating cantilever 2509 is oscillated by passing an oscillating current through the probe as described previously.

FIG. 26 shows a finite element model that was used to estimate the field strength and directions in the vicinity of the

self-heating cantilever (2601). Fields as high as 0.2 T can be achieved with a clearance of ~0.5 mm between the pole piece (2603) and the cantilever. To achieve these fields a high permeability ferromagnetic material, for example HyMu 80 with a permeability of around 230,000, may be employed.

The Lorentz drive has a significant advantage over conventional piezo drive schemes. FIG. 27 shows a comparison of the resonant peaks detected with a piezoelectric drive mechanism (top) versus the Lorentz drive (bottom) on the same polymer sample and the same location. The Lorentz drive (bottom) shows clear, well defined resonances. The piezo drive spectrum shows a confusing mix of real cantilever resonances distorted by and mixed with mechanical resonances of other parts of the AFM system. As such, it can be very difficult to interpret the resonances in a piezo driven system and be confident that the resonances are only due to cantilever and material properties.

With this Lorentz drive mounted in the AFM head, it is possible to measure a wide range of samples. FIG. 28A shows an AFM height measurement taken across a polymer blend containing polystyrene (PS) and low density polyethylene (LDPE). The crosshairs indicate the positions where broadband mechanical spectra were obtained, as shown in FIGS. 28B and 28C. These broadband mechanical spectra were measured from DC to 1 MHz. The measurements shown were performed in 10 sec per sweep. The inventors have also performed sweeps in times of 1 sec, 0.1 sec and 0.01 sec. These broadband mechanical spectra provide rich information about the sample. By measuring the free resonance spectrum of the AFM cantilever, it is possible to characterize the free oscillation modes of the cantilever. Then when the cantilever tip touches a sample surface these oscillation modes transform into contact resonance modes whose frequencies and quality factors depend on the mechanical properties of the sample. Specifically the vertical and lateral contact stiffness and vertical and lateral damping forces shape the contact resonance mechanical spectra. By analyzing the shifts between free resonances and contact resonances, it is possible to extract values for the vertical and lateral contact stiffnesses and damping forces. Hurley, Yablon and colleagues have also demonstrated the ability to extract viscoelastic parameters like storage modulus, loss modulus and tan δ from contact resonance curves. The current Lorentz drive scheme provides the opportunity to substantially improve these measurements for two key reasons. First, the clean mechanical spectra give unambiguous measurements of the true cantilever resonances, independent of all mechanical resonances of other parts of the AFM. Second, the Lorentz drive scheme can be used to excite both flexural and torsional resonance modes. Flexural resonant frequencies can be highly dependent on both the sample's vertical stiffness and lateral stiffness. This can cause difficulty in interpreting shifts in the flexural resonance frequencies as it can be difficult to determine if the shifts are due to variations in vertical stiffness or uncontrolled lateral forces. The torsional resonance frequencies on the other hand, are mostly dependent on the lateral forces and lateral sample stiffnesses. Since the Lorentz drive scheme can also excite torsional resonances (through forces acting on the cantilever arms, for example), this technique can make it possible to separately evaluate the lateral forces and then appropriately extract vertical stiffness from the flexural resonance frequencies. This can overcome a major limitation of conventional contact resonance where the lateral forces may not be well known, thus resulting in substantial errors in vertical stiffness calculations.

The Lorentz drive scheme can also be tuned to provide high contrast material maps. It is possible to perform a frequency

sweep (as described previously) to determine one or more contact resonance frequencies as a function of position on a sample and/or as a function of temperature. Additionally it is possible to tune the Lorentz drive frequency to a specific frequency that provides high contrast between two materials. FIG. 29 for example shows Lorentz contact resonance measurements of the same PS-LDPE sample mentioned in connection with FIGS. 28A-C. In this case FIG. 29A image shows the height map, FIG. 29B shows the cantilever amplitude and FIG. 29C shows the phase response as at a selected drive frequency. These measurements were performed at 265 kHz, corresponding to the 2nd flexural resonance of the cantilever employed, as indicated in the mechanical spectrum in 29D Other frequencies can be chosen to highlight differences in lateral forces (for example from friction) by selecting appropriate torsional oscillation modes that provide contrast between the materials of interest.

Because we can employ self-heating cantilevers for the Lorentz drive scheme, the current invention can be used to measure the temperature dependence of mechanical spectra and hence the temperature and frequency dependence of sample material properties. FIG. 30 shows an example of measuring broadband mechanical spectra at different temperature on a blend of polystyrene and PMMA. These spectra are rich in information about the temperature dependence of the sample. First, at low frequencies (below the first resonance, for example), it is possible to directly visualize the temperature dependent stiffness of the sample as at higher temperatures the sample allows increased penetration of the AFM tip into the sample and thus greater oscillation amplitudes. At higher frequencies, the change in vertical and lateral stiffnesses can be determined by shifts in the resonance frequencies of different oscillation modes. Analysis of these curves also allows determination of the frequency dependent changes in mechanical properties. Each oscillation mode can be analyzed to determine the vertical and lateral stiffness that provides a resonance at the detected frequency. Thus a plot of stiffness versus frequency can be obtained for many decades of frequency, from around DC to 1 MHz or higher.

FIG. 31 shows an example of composition mapping using Lorentz contact resonance. The sample is a biopolymer composite. The top plots show height and flexural amplitude measurements at the cantilevers' 2nd flexural resonance. The plots below show subsets of broadband mechanical spectra showing flexural and torsional resonances at three locations on the biopolymer composite. FIG. 32 is another suite of compositional maps obtained with Lorentz contact resonance. The sample is a preparation of asphalt. The height images show stress induced ripples from the sample processing. In the Lorentz contact resonance amplitude image it is also possible to see phase domains with two clearly distinct materials, including islands around the stress ripples. The Lorentz contact resonance image reveals radial stress features that emanate from the stress feature to the edges of the islands. The Lorentz contact resonance Phase image clearly resolves the ripples and the differences between the islands and the surrounding matrix material, but does not see the radial stress features. As such, it is clear that the Lorentz contact resonance measurements can sample independent aspects of the material properties of the sample.

FIG. 33 shows an example of mechanical spectra obtained by Lorentz drive with the tip in contact (On surface) and out of contact (Off surface) with a sample. Analysis of the mode frequency shifts between these two spectra can be used to extract vertical and lateral contact stiffness and damping as described above.

FIG. 34 shows an example calculation of mode frequencies versus relative contact stiffness with differing values of lateral forces. These calculations are modeled after analytical calculations by Rabe et al. It is possible to construct models from either analytical calculations or finite element models to fit a pattern of measured mode frequencies. These models can allow extraction of the vertical and lateral stiffnesses that give rise to the observed mode resonances.

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- Statements Regarding Incorporation By Reference And Variations

All references throughout this application, for example patent documents including issued or granted patents or equivalents; patent application publications; and non-patent literature documents or other source material; are hereby incorporated by reference herein in their entireties, as though individually incorporated by reference, to the extent each reference is at least partially not inconsistent with the disclosure in this application (for example, a reference that is partially inconsistent is incorporated by reference except for the partially inconsistent portion of the reference).

All patents and publications mentioned in the specification are indicative of the levels of skill of those skilled in the art to which the invention pertains. References cited herein are incorporated by reference herein in their entirety to indicate the state of the art, in some cases as of their filing date, and it is intended that this information can be employed herein, if needed, to exclude (for example, to disclaim) specific embodiments that are in the prior art. For example, when a compound is claimed, it should be understood that compounds known in the prior art, including certain compounds disclosed in the references disclosed herein (particularly in referenced patent documents), are not intended to be included in the claim.

When a group of substituents is disclosed herein, it is understood that all individual members of those groups and all subgroups and classes that can be formed using the substituents are disclosed separately. When a Markush group or other grouping is used herein, all individual members of the group and all combinations and subcombinations possible of the group are intended to be individually included in the disclosure. As used herein, “and/or” means that one, all, or any combination of items in a list separated by “and/or” are included in the list; for example “1, 2 and/or 3” is equivalent to “‘1’ or ‘2’ or ‘3’ or ‘1 and 2’ or ‘1 and 3’ or ‘2 and 3’ or ‘1, 2 and 3’.”

Every formulation or combination of components described or exemplified can be used to practice the invention, unless otherwise stated. Specific names of materials are intended to be exemplary, as it is known that one of ordinary skill in the art can name the same material differently. One of ordinary skill in the art will appreciate that methods, device elements, starting materials, and synthetic methods other than those specifically exemplified can be employed in the practice of the invention without resort to undue experimentation. All art-known functional equivalents, of any such methods, device elements, starting materials, and synthetic methods are intended to be included in this invention. Whenever a range is given in the specification, for example, a temperature range, a time range, or a composition range, all intermediate ranges and subranges, as well as all individual values included in the ranges given are intended to be included in the disclosure.

As used herein, “comprising” is synonymous with “including,” “containing,” or “characterized by,” and is inclusive or open-ended and does not exclude additional, unrecited elements or method steps. As used herein, “consisting of” excludes any element, step, or ingredient not specified in the claim element. As used herein, “consisting essentially of” does not exclude materials or steps that do not materially affect the basic and novel characteristics of the claim. Any recitation herein of the term “comprising”, particularly in a description of components of a composition or in a description of elements of a device, is understood to encompass those compositions and methods consisting essentially of and consisting of the recited components or elements. The invention illustratively described herein suitably may be practiced in

the absence of any element or elements, limitation or limitations which is not specifically disclosed herein.

The terms and expressions which have been employed are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed. Thus, it should be understood that although the present invention has been specifically disclosed by preferred embodiments and optional features, modification and variation of the concepts herein disclosed may be resorted to by those skilled in the art, and that such modifications and variations are considered to be within the scope of this invention as defined by the appended claims.

We claim:

1. A device for characterizing a region of a sample with sub-micron spatial resolution, the device comprising:
a self-heating cantilever probe having a tip;
a magnetic source placed in proximity to the cantilever probe; and
a current source in communication with the self-heating cantilever.
2. The device of claim 1, further comprising a deflection measurement system and a demodulator.
3. The device of claim 1, wherein the magnetic source comprises a permanent magnet coupled to a magnetic pole piece.
4. The device of claim 3, wherein the magnetic pole piece has a permeability of more than 10,000.
5. The device of claim 3, wherein the magnetic source and the magnetic pole piece generate a magnetic field having a strength of at least 0.2 T at the self-heating cantilever probe.
6. The device of claim 1, wherein the magnetic source comprises a magnet and wherein the magnet is positioned on or in a slot, thereby permitting sliding the magnet between at least two locations.
7. The device of claim 6, wherein the at least two locations include (a) a first location to maximize a magnetic field at the self-heating cantilever probe and (b) a second location to permit exchanging or removal of the self-heating cantilever probe.
8. The device of claim 1, wherein the current source is configured to ramp the self-heating cantilever probe through a plurality of temperatures.
9. The device of claim 1, wherein the current source is configured to include an AC current component that generates an oscillating force on the self-heating cantilever probe.
10. The device of claim 9, wherein the current source is configured to generate AC currents over a plurality of frequencies.
11. The device of claim 2, further comprising a resonance tracker to determine a resonance of the self-heating cantilever probe.
12. The device of claim 11, further comprising a system for calculating one or more viscoelastic properties of a sample based on a resonance of the self-heating cantilever probe.
13. The device of claim 10, wherein AC currents generated at a plurality of frequencies are used to create a spectrum of the self-heating cantilever probe response versus frequency.

14. The device of claim 13, where the spectrum of the self-heating cantilever probe response versus frequency is substantially devoid of parasitic mechanical resonances.
15. The device of claim 9, wherein the AC current comprises an AC frequency component in excess of 1 GHz.
16. The device of claim 15, wherein the self-heating cantilever probe exerts a force on a sample at a frequency in excess of 1 GHz.
17. The device of claim 3, further comprising a system for calculation of a plastic deformation property of a region of a sample based on a resonance of the self-heating cantilever probe.
18. The device of claim 17, wherein the plastic deformation property comprises one or more of a yield strength of the sample, a hardness of the sample and a creep of the sample.
19. The device of claim 3, further comprising a system for calculation of one or more glass transition temperature properties of a region of a sample based on a resonance of the self-heating cantilever probe.
20. A method of determining a material property of a sub-micron region of a sample, the method comprising the steps of:
interacting a probe tip of a self-heating cantilever probe with a surface of the sample;
applying a force between the probe tip and the surface of the sample, wherein the force is generated by an interaction between a current through the self-heating cantilever probe and a magnetic field;
measuring a response of the self-heating cantilever probe to the applied force; and
determining the property of a sub-micron region of the sample from the measured response.
21. The method of claim 20, wherein the material property comprises one or more of a plastic deformation property, a yield strength, a hardness, a creep, a glass transition temperature, a melting temperature, a viscoelastic property and a stiffness.
22. The method of claim 20, further comprising a step of heating at least the sub-micron region of the sample by passing a current through the self-heating cantilever probe.
23. The method of claim 22, wherein the step of heating at least the sub-micron region of the sample occurs during the step of applying a force between the probe tip and the surface of the sample.
24. The method of claim 22, further comprising repeating the interacting, applying, measuring and heating steps one or more times to measure a response of the self-heating cantilever probe at a plurality of temperatures of the sub-micron region of the sample.
25. The method of claim 20, wherein the response of the self-heating cantilever probe comprises one or more of a cantilever deflection, a contact resonance frequency, an amplitude, a phase, an in-phase amplitude (X), and a quadrature amplitude (Y).
26. The method of claim 20, further comprising repeating the interacting, applying and measuring steps at a plurality of locations of the surface of the sample.