Micron-scale displacement measurement devices having enhanced performance characteristics are disclosed. One embodiment of a micron-scale displacement measurement device includes a phase-sensitive reflective diffraction grating for reflecting a first portion of an incident light and transmitting a second portion of the incident light such that the second portion of the incident light is diffracted. The device can further include a mechanical structure having a first region and a second region, the mechanical structure positioned a distance d above the diffraction grating and forming a wall of a cavity. The second portion of the incident light is reflected off of the first region of the structure such that an interference pattern is formed by the reflected first portion and the reflected second portion of the incident light. The device can further include an orifice formed in the cavity to provide for the passage of air between the inside and outside of the cavity.


John Baliga; “Polymer Pillars for Optical and Electrical Signals”; Semiconductor International; Dec. 2004; p. 36.


* cited by examiner
FIG. 6

Remote located light source and detectors

FIG. 7
Illuminate Membrane Through Tunable Diffraction Grating

Receive Interference Patterns

Measure Intensity of the Interference Patterns

Calculate Distance $d$

Calibrate/Modulate Diffraction Grating Fingers with $V_{AC}$

Optimize Sensitivity with $V_{DC}$

Actuate Gratings

FIG. 8
DISPLACEMENT-MEASURING OPTICAL DEVICE WITH ORIFICE

CROSS-REFERENCE TO RELATED APPLICATIONS


This application is related to co-pending commonly assigned Non-Provisional application entitled, “System and Method for Surface Profiling,” filed concurrently herewith on Apr. 17, 2006, and accorded Ser. No. 11/405,051.

TECHNICAL FIELD

The present disclosure generally relates to measurement devices. More specifically, the disclosure relates to highly-sensitive, micron scale, displacement measurement devices.

DESCRIPTION OF THE RELATED ART

Hearing aids, for example, provide specific applications in which micromachined capacitive microphones. The electrical sensitivity of the microphone, $S_e$, is defined as the change in voltage output per change in membrane displacement. In a similar fashion, the mechanical sensitivity, $S_m$, is defined as the change in membrane displacement per change in applied pressure (i.e. $S_m$ is simply the compliance or softness of the membrane). The total sensitivity of the device to sound pressure can then be expressed as $S_e x S_m$, with units of Volts/Pa. For high $S_e$, a large DC bias voltage should be applied and the gap height between the electrodes should be made as small as possible, typically on the order of 2 $\mu$m. These attributes are, in fact, in conflict, as the maximum DC bias that can be used is limited by the electrostatic collapse voltage, which decreases with shrinking gap height. The electrical sensitivity is a maximum when the device is biased near this electrostatic collapse voltage. Unfortunately, the detection scheme becomes non-linear under this same condition. In addition to this drawback, implementation of the constant charge condition can require the use of high impedance amplifiers, which come with high electronic noise. To compensate for poor $S_e$, micromachined capacitive microphones use large, soft membranes on the order of 1-5 mm to enhance mechanical sensitivity and, in turn, the overall device performance. Even this approach is limited, however, by membrane stresses that result during fabrication. These stresses bound the mechanical sensitivity that can be achieved and make the fabrication of uniform membranes with high yield difficult. In addition to using a soft membrane, the back electrode can be perforated and open to a large backside cavity to prevent additional stiffening which would otherwise occur from compression of the air in the thin gap. The perforation reduces the active capacitance and adversely affects $S_m$, leading to yet another design conflict. In summary, the electrical and mechanical sensitivity in a micromachined capacitive microphone are not independent and impose severe design and fabrication limitations.

Optical interferometry is the act of splitting and recombing electromagnetic waves, in particular, visible light waves, to measure surface geometries, distance, etc. The advancement in interferometry has come in many avenues of technology. Long-range telescopes, high-resolution spectrometers, compact disc players, etc., use some form of interferometry. Micro-machinery is a growing technology field that often utilizes interferometers because they typically have high resolution and precision. In general, displacement measurements in the sub-nanometer range can be detected with today’s interferometers. To examine microscale structures, the lateral resolution of the interferometers, generally, need to be improved. This can be achieved by coupling the interferometer to a regular microscope. Unfortunately, the size of the interferometer becomes rather large and subsequently may not fit in small spaces for inspection. Furthermore, to inspect a large number of microscale structures either the sample or microscope objective is scanned, resulting in slow imaging.

In order to obtain interferometric measurement sensitivity in a small volume, several methods have been developed. One of these methods involves phase sensitive diffraction gratings as described in a paper written by E. B. Cooper, E. R. Post, and S. Griffith and entitled “High-resolution micromachined interferometric accelerometer,” Appl. Phys. Lett., 76 (22), pp. 3316-3318, May 29, 2000. Both of these papers are incorporated by reference in their entireties.

Based on the foregoing, it would be desirable to incorporate optical interferometry with micro-machined microphone technology so as to improve over the current prior art. Furthermore, it would be desirable to explore other aspects in which highly-sensitive, micron-scale displacement measurement devices may be utilized.

SUMMARY

Micron-scale displacement measurement devices having enhanced performance characteristics are disclosed.

An embodiment of a device includes a phase-sensitive reflective diffraction grating for reflecting a first portion of an incident light and transmitting a second portion of the incident light such that the second portion of the incident light is diffracted. The device can further include a mechanical structure having a first region and a second region, the mechanical structure positioned a distance $d$ above the diffraction grating and forming a wall of a cavity. The second portion of the incident light is reflected off of the first region of the structure such that an interference pattern is formed by the reflected first portion and the reflected second portion of the incident light. The device further includes an orifice in the cavity to provide for the passage of air between the inside and outside of the cavity.
An embodiment of a method comprises equalizing the air pressure between an inside and an outside of a cavity, the cavity including a wall comprising a mechanical structure having a first region and a second region. The method further comprises illuminating a reflective diffraction grating with an incident light, the diffraction grating being positioned a distance $d$ from the mechanical structure, a first portion of the incident light being reflected and a second portion of the incident light transmitted through the diffraction grating such that the second portion of the incident light is diffracted. The method can further include reflecting the second portion of the incident light off of the first region of the mechanical structure such that an interference pattern is formed by the reflected first portion and the reflected second portion of the incident light.

An embodiment of a device comprises means for equalizing the air pressure between an inside and an outside of a cavity, the cavity including a wall comprising a mechanical structure having a first region and a second region. The device further includes means for illuminating a reflective diffraction grating with an incident light, the diffraction grating being positioned a distance $d$ from the mechanical structure, a first portion of the incident light being reflected and a second portion of the incident light transmitted through the diffraction grating such that the second portion of the incident light is diffracted. The device can further include means for reflecting the second portion of the incident light off of the first region of the mechanical structure such that an interference pattern is formed by the reflected first portion and the reflected second portion of the incident light.

Other devices, methods, features, and advantages of the present invention will be or become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the present invention, and be protected by the accompanying claims.

**DETAILED DESCRIPTION**

As will be described in greater detail herein, displacement measurement devices in accordance with the present disclosure can measure the change in position of a membrane as a function of time due to a variety of factors. Furthermore, the displacement measurement devices can be optimized for displacement sensitivity and reduced noise causing a greater signal to noise ratio (SNR).

Referring now in more detail to the drawings, FIG. 1 is a diagram illustrating the concept of using a diffraction grating to split beams in a microinterferometer. This concept has been utilized in measuring precise relative displacements, such as for the measurement of Atomic Force Microscopy (AFM) tip displacement and in spatial light modulators, as in the grating light valves (GLV). This concept is also disclosed in U.S. Pat. No. 6,567,572 entitled “Optical Displacement Sensor” to F. L. Degertekin, G. G. Yaralioglu, and B. Khuri-Yakub, which is incorporated by reference in its entirety. AFM, in general, is a technique for analyzing the surface of a rigid material at the atomic level. AFM uses a mechanical probe to magnify surface features up to $100,000,000$ times, and it can produce 3-D images of the surface. In general, a GLV contains several tiny reflective ribs that are mounted over a silicon chip with a tiny air gap in between the chip and the ribs. When a voltage is applied to the chip below a particular ribbon, that ribbon bends toward the chip by a fraction of a wavelength of an illuminating light. The deformed ribs collectively form a diffraction grating and the various orders of the light can be combined to form the pixel of an image. The shape of the ribs, and therefore the image information, can be changed in as little as 20 billionths of a second.

The diagram of FIG. 1 illustrates two scenarios. A first scenario 1 shows what occurs when a target surface 4 is placed a distance of a half-wavelength, $\lambda/2$, away from a reference point, in this case, a reflective diffraction grating 5. A second scenario 2 shows what occurs when the target surface 4 is placed a distance of a quarter-wavelength, $\lambda/4$, away from the diffraction grating 5. The detailed diffraction pattern of such a structure can be found by applying standard diffraction theory to determine the locations and the dimensions of the photo-detectors or light guide apertures.

In both instances, the reflective diffraction grating 5 is formed on a transparent substrate 3. Exemplary materials that may be utilized to construct such elements will be discussed in further detail in relation to FIG. 4. The diffraction grating 5 is formed of an array of diffraction grating fingers 6 equally spaced along a front edge of the transparent substrate 3. It should be noted that, as mentioned above, this diagram is not
to scale, and is merely for illustrative purposes. In reality, the diffraction grating fingers 6 would typically have a height on the order of micro- or nano-meters.

In the first scenario 1, when an incident light is illuminated through the transparent substrate 3, a first portion of the incident light is reflected from the reflective diffraction grating 5. A second portion of the incident light is transmitted and diffracted about the diffraction grating fingers 6. The transmitted and diffracted light reflects off of the target surface 4 and is measured by a proper detection unit (not shown), such as a photo-detector or a photo-diode. As in scenario 1, the target surface is placed at a distance of $\lambda/2$ or any integer multiple thereof. In this case, the 0th order of the transmitted incident light is reflected back. In general, the 0th order is the transmitted light that is illuminated directly, in which case no diffraction, or change in direction occurs. The first portion of the incident light, and the second portion of the incident light which has been reflected off of the target surface 4 interferes with each other. The phase of the two portions of the light waves help form constructive and destructive interference patterns. From the interference patterns, the relative distance between the diffraction grating 5 and the target surface 4 can be determined.

In scenario 2, the same general structure is set up. In this case, the target surface 4 is placed a distance of $\lambda/4$ away from the diffraction grating 5. In practice, the target surface 4 may be placed at any integer multiple of $\lambda/4$ and the same general results will occur. When the first portion of the incident light joins with the second portion of the incident light upon reflection, destructive interference cancels out the two. The second portion of the light travels an extra distance of $2x$ the distance between the target surface 4 and the diffraction grating 3, which results in a phase difference between the two portions of $\pi$, complete destructive interference. On the contrary though, the higher order diffraction fields, such as the first order, can constructively interfere with the first portion of the incident light. As FIG. 1 depicts, the higher order first and second portions of the incident light are angled and not parallel to the line of illumination, like the 0th order beam.

Having described an example of using a diffraction grating to split light beams and therefore measure relative distance, theoretical calculations will be utilized to show the results of using the method described in FIG. 1. Suppose an incident light of $\lambda = 632$ nm is illuminated through the transparent substrate 3 onto the reflective diffraction grating 5. A laser can be utilized to provide the incident light. In this case, a helium-neon (HeNe) laser can be utilized. Suppose the diffraction grating 5 contains 10 diffraction grating fingers 6 equally spaced at $d_p = 2$ µm. FIG. 2 is a graph 10 illustrating the distribution of reflected light measured on an observation plane with various gap thicknesses utilizing the method illustrated in FIG. 1. Hereinafter, the distance between a reference point, in this case the diffraction grating 5, and the target surface 4 will be referred to as the gap thickness and can be considered the absolute distance to the surface.

FIG. 2 shows the normalized intensity of reflected light 20 versus an observation length, x. The observation length, x, is in the lateral direction, and centered at the 0th order beam. In this case, a 100 µm wide photo-detector has been used. Three scenarios are shown in the graph 10. Scenario 12 shows the normalized intensity 20 with gap thickness, $d = \lambda/2$. Scenario 14 shows the normalized intensity 20 with gap thickness, $d = \lambda/4$. Scenario 16 shows the normalized intensity 20 with gap thickness, $d = \lambda/8$.

As expected, scenario 12 shows the 0th order reflected beam with complete constructive interference. The higher order beams, e.g. the 1st and 3rd order beams, incur destructive interference and so their intensity is cancelled out. Scenario 14 shows that the 0th order has been completely cancelled out and the 1st and the 3rd orders of the reflected beam appear to have partial intensity. Scenario 16 shows that when the gap thickness, $d = \lambda/8$, both the 0th order and the 1st order contain some light intensity. Perhaps, most importantly, graph 10 attempts to show the periodic nature of the intensity of the reflected orders of the incident light versus varying gap thickness.

The intensity of these orders as a function of grating-reflecting surface shows the $\cos^2(2\pi d/\lambda)$ and $\sin^2(2\pi d/\lambda)$ variation, as illustrated in FIG. 3. FIG. 3 is a graph 30 illustrating the normalized intensity 38 of various diffraction orders 32 and 34 versus gap thickness 36 utilizing the method described in FIG. 1.

As shown in FIG. 3, the 0th order curve 32 takes on a $\cos^2(2\pi d/\lambda)$ shape. This is in line with the results found in FIG. 2. At gap thickness of $\lambda/2$, which is approximately 0.316 µm, the intensity is greatest. At gap thickness of $\lambda/4$, which is approximately 0.158 µm, the intensity is zero. The 1st order curve 34 takes on a $\sin^2(2\pi d/\lambda)$ shape. The graph 30 of FIG. 3 clearly displays the periodic nature of the diffraction orders. As one can see, keeping all other variables constant and known, one can calculate the relative distance by measuring the intensity of the orders, in particular the 1st order. In fact, by monitoring the intensity of any of the reflected orders, one can achieve interferometric resolution on the order of $1 \times 10^{-15}$ $\lambda^2/\text{Hz}$.

The present disclosure provides a sensitive diffraction-based optical displacement apparatus and method to measure the static and dynamic displacement of reflectors in various applications. The present disclosure includes the use of any type of reflector, however, in a preferred embodiment, the present disclosure includes a flexible and optically reflective membrane. The apparatus and method of the present disclosure is amenable to integration of electronics and optics to form compact displacement detectors for a single membrane or membranes fabricated in the form of arrays. Typical applications of the present disclosure would be in, for instance, but not limited to, microphones (micro-machined or not), micro-machined ultrasonic transducers, micro-machined ultrasonic wave generators, micro-machined ultrasonic image applications, pressure sensors and hearing aids. The embodiments of the present disclosure would also be useful in any sensing application where the position of a reflector or membrane is changed due to a chemical or physical process and this displacement needs to be measured accurately in a broad frequency range. Furthermore, the embodiments of the present disclosure would also be useful in any sensing application where the reflectivity of a reflector or a membrane is changed due to a chemical or physical process and this change needs to be measured accurately in a broad frequency range.

U.S. Pat. No. 6,567,572 entitled “Optical Displacement Sensor” discloses various embodiments of a micro-machined optical displacement sensor. For example, FIG. 4 of U.S. Pat. No. 6,567,572 illustrates an optical displacement sensor that includes a reflective diffraction grating 430 deposited upon a transparent substrate 420. Suspended above the diffraction grating 430 is a reflector 410. A voltage bias is applied across the reflector 410 and diffraction grating 430 so as to electrostatically actuate the reflector 410 to vary its position and/or rigidity.

An improvement to the sensor of U.S. Pat. No. 6,567,572 is embodied in the present disclosure. That is to add a semi-transparent layer to the top of the transparent substrate 420. This mirror layer can be built using a thin metal film and a dielectric stack of alternating quarter-wave thick media. Preliminary testing shows the thickness of the mirror layer and
the reflectivity of the metal used can greatly increase the sensitivity of the sensor. To complement the mirror layer placed on the transparent substrate 420 would be the reflective surface of the reflective membrane 410. Similar testing of the thickness of the mirrored reflective layer of the membrane 410 and the material used proved complimentary results, however, keeping in mind that added thickness and the various materials used can affect the rigidity of the reflective membrane 410.

FIG. 4 is a diagram illustrating a first embodiment of a micro-displacement measurement device 100 in accordance with embodiments of the present disclosure. As shown in FIG. 4, the embodiments of the present disclosure provide for the use of a tunable, phase-sensitive diffraction grating 156 mounted above substrate 160 to measure the displacement of the membrane structure 150. A light source 140 is integrated in the device 100 to provide an incident light beam to be shined on the reflective diffraction grating 156 and the reflective membrane 150. A photo-detector 120 is positioned to receive the interference pattern produced by the reflected light beams. The embodiments of the present disclosure are not limited to the number of photo-detectors. In addition, the present disclosure includes another embodiment where the photo-detectors are one or more optical fibers. The main part of the device 100 consists of a flexible optically reflective membrane 150 suspended above a non-moving, transparent substrate 160. For displacement detection, the intensity of the light 101 from light source 140 reflected from the membrane 150 and reflective diffraction grating 156 is monitored. Grating 156 consists of periodic reflective fingers positioned atop transparent, yet conductive, electrodes 180 which are deposited atop the transparent substrate 160. Displacement of membrane 150 changes the intensity of the diffraction orders 104 which can be easily detected using standard photo-detector(s) 120. This provides the sensitivity of an optical interferometer, and has a better noise performance as compared to other intensity based commercial optical microphones. Light source 140 provides incident light beam 101 through substrate 160 to reflective membrane 150. Reflective membrane 150 is positioned to diffraction grating 156 at an odd multiple of a quarter of the wavelength of light source 140. In addition, the device 100 could include a wafer (not shown), preferably a silicon wafer for housing the light source 140 and/or the photo-detector 120.

In order to realize a sensitive microphone one should have a compliant membrane, which can be displaced by pressure fields and a detection scheme to detect membrane displacements at the pressure levels in the order of 10^{-5} Pa. The pressure equivalent of the thermal mechanical noise of the membrane structure should be small since this number determines the minimum detectable pressure level. It is preferable that a broadband microphone have a membrane response free of resonances in the bandwidth of interest and a broadband detection scheme. The micro-machined microphone membrane and the integrated optical detection scheme satisfy these preferred attributes. The device can also transmit sound and can be self-calibrating by the application of bias voltages between the electrodes 180 and grating 156. In the following description, the elements and operation of the microphone are discussed in detail.

The light source 140, in this embodiment, may be a laser, that emits an electromagnetic wave at a known wavelength, \( \lambda \). An emitted incident light beam 101 would be illuminated onto the reflective diffraction grating 156. In this embodiment, a Helium-Neon (HeNe) laser (\( \lambda \approx 632 \text{ nm} \)) may be utilized. In other embodiments, the light source 140 may be a laser emitting another known wavelength. The exact wavelength of the incident light beam 101 may vary as long as the dimensions of the components of the device 100 are calculated in terms of the incident light beam 101 wavelength. To that, light sources emitting more than one known wavelength can be utilized as well, although, preferably, a light source emitting one known wavelength would be utilized. In practice, any kind of temporarily coherent light source with a coherence length equal to or greater than two times the distance between the membrane 150 and the diffraction grating 156 may be utilized. The light source 140 may also be a Vertical Cavity Surface Emitting Laser (VCSEL) mounted on a wafer or printed circuit board.

In other embodiments, the incident light beam 101 may be carried via an optical fiber, in which case the light source 140 may be located remotely. As depicted in FIG. 4, the light source 140 is positioned normal to the plane of the transparent substrate 160. Utilizing an optical fiber adds flexibility in placing the light source 140.

In yet other embodiments, the incident light beam 101 may be guided towards the diffraction grating 156 via a wave guide and/or a set of properly placed mirrors. For instance, the light source 140 may be placed relatively parallel to the lengthwise direction of the transparent substrate 152. In this case, a mirror and/or a wave guide can change the direction of the incident light beam 101 so that it is illuminated at a direction normal to the diffraction grating 156. To that, although it appears that the best results occur when the incident light beam 101 is illuminated at a direction normal to the diffraction grating 156, it need not be necessary. Other wave shaping instruments may be utilized, such as microlens, to collimate the incident light beam 101. The reflected light beams 104 may also be shaped by a system of wave shaping instruments.

The transparent substrate 160 is typically a planar surface, although not necessarily. For example, the substrate 160 may be cut so as to have a rounded surface for the forming the diffraction grating 156. This may aid in focusing the incident light beam 101. A variety of materials can be utilized for the substrate 160. Non-limiting examples are quartz, silicon, sapphire, glass, and combinations thereof. In other embodiments, the substrate 160 may be non-transparent, but a bulk-etched cavity may be incorporated into the substrate 160 to allow illumination. In general, the transmission coefficient, \( \tau \), of the transparent substrate 160 for a given wavelength of incident light beam 101 may be larger than 0.9: the dimensions of the transparent substrate 160 can vary according to the overall structure of the device 100, but in general, the lateral thickness of the substrate 160 may be in the range of 0.1 mm-2 mm, and likewise having a working distance of 0.1 mm-2 mm with an F-number from 1 to 5. The lateral length can vary with the structure of the device 100. In other embodiments, the transparent substrate 160 may be configured, upon manufacture, to assist in focusing the diffracted and/or collimated incident light beams.

In an alternative embodiment, the displacement sensitivity can be improved by fabricating a semi-transparent mirror layer on the top surface of the transparent substrate 160. As mentioned, the diffraction grating 156 may include several equally spaced fingers. In general, the spatial separation between adjacent fingers may be on the order of the wavelength of the incident light beam 101. The fingers may be constructed of a reflective and conductive material that has a reflection coefficient of between 0.8 to 1. The conductivity of the diffraction grating fingers may be necessary for electrostatic actuation of the fingers. In general, the fingers may be shaped as blocks and could also be composed of a conductive material with a non-dielectric reflective coating. In other
embodiments, the fingers may be composed of a dielectric material and be coated with a conductive reflective material. The dimensions of the fingers can vary greatly with the wavelength of the incident light beam. In this embodiment, however, the dimensions of the fingers may be on the order of the wavelength of the incident light beam, or about 0.5 μm to 10 μm. Several fingers (on the order of 10, in lateral length) may make up the diffraction grating. In this embodiment, the diffraction grating is formed above the top planar surface of the transparent substrate.

The diffraction grating fingers need not be equally spaced. The diffraction grating may be configured to focus the incident light beam to a given focal point. This may be accomplished by varying the spacing between the fingers in such a way as to focus the light.

The electrodes are placed in relation to the diffraction grating fingers. In general, the electrodes are a conductive material that is deposited onto the substrate. Similar to the diffraction grating fingers, the electrodes may be a dielectric material covered with a conductive coating. The electrodes may also be made of a transparent material coated or doped with a conductive material.

The device also includes a photo-detector. In this embodiment, the photo-detector may be placed parallel and underneath the substrate. As the figure depicts, the photo-detector may be positioned to receive a higher diffraction order of the reflected light, such as the 1st or 3rd order. The observation length, x, can vary, but should be properly positioned so that a higher diffraction order may be observed.

In other embodiments, the photo-detector may be remotely located and the diffracted light may be received via an appropriately placed optical fiber. In yet other embodiments, a wave guide and/or mirrors may change the direction of the diffracted and reflected beams. In this embodiment, as mentioned, the photo-detector is placed parallel to the substrate. This allows for a relatively small space, on the order of 100 μm-1000 μm.

Several photo-detectors are known in the art. In general, any photo-detector that can be configured for micro-machining and can sustain the desired bandwidth can be utilized. One specific example of a photo-detector that can be used is a silicon P-N junction photodiode. Another type that could be utilized is a P-I-N type photodiode. The utilized photo-detector may depend on the processing speed and responsivity (photocurrent per Watt of incident light) requirements. For example, at wavelengths where the absorption of silicon is small, deeper junction depths may be used to increase responsivity.

Similarly, the geometry of the photo-detector may be adjusted to minimize its capacitance and transit time to increase the detection bandwidth. Some signal conditioning circuitry, such as a transimpedance amplifier, may also be implemented on the same semiconductor substrate as the photo-detector to minimize noise and decrease parasitic capacitance. These photo-detectors with integrated electronics can be configured to operate with bandwidths from DC to GHz range for sensing optical communication applications.

A processor may be included within the device, but more likely will be communicatively coupled to the photo-detector and be an external component. The processor may be any type of electrical component that can process the signals received by the photo-detector. Like-wise, hardware, software, and/or firmware may be utilized to properly make the appropriate calculations. For example, a personal computer may be configured to process the signals received from the photo-detector in data that is compiled and calculated to produce the change in distance d as a function of time. A relatively simple digital signal processor (DSP) or an application specific integrated circuit (ASIC) may be utilized to perform the calculations. The processor may also be capable of making several other calculations and/or perform other functions, such as calibration, laser intensity normalization, digital filtering, and signal conditioning.

Coupled to the diffraction grating and electrodes is a controller for controllably adjusting, in this embodiment, the position of the diffraction grating. This is accomplished by electrostatic actuation which is discussed below. The controller may be communicatively coupled to the processor. In this manner, force-feedback approaches to measuring the distance d can be accomplished.

The structure of the devices of the present disclosure include a phase sensitive optical diffraction grating, in which the diffraction pattern is determined by the membrane displacement relative to the diffraction grating (which position can vary, to be discussed below). The incident light will be reflected back to the zeroth order when the gap thickness is an integer multiple of λ/2, and to the odd diffraction orders when the gap thickness is an odd multiple of λ/4. Notably, as illustrated in FIG. 3, the change in intensity of both orders per gap thickness is maximized in a periodic fashion in these multiples. Operating the device at the point of maximum change in intensity (the slope of the cos and sin curves of FIG. 3) is beneficial because it maximizes the sensitivity of the device.

As illustrated in FIG. 4, the photo-detector is positioned to receive the first order, which has maximum change in intensity at odd multiples of λ/4. Notably, when a single photo-detector is used to detect the intensity of a diffraction order the output signal will include the effect of laser intensity noise degrading the performance of the device. This noise can be eliminated by normalizing the output signal with the laser output power. By way of using arrays of these devices to form a microphone, the noise level will be further reduced by spatial averaging.

In order to operate the device at the maximum sensitivity and to adjust for the ambient pressure changes, there can be a DC bias voltage applied between electrodes and grating. Adding an AC signal to the bias, the device can be used as a regular CMUT, which can transmit sound as well as receive acoustic signals. The DC and AC voltages electrostatically actuate the grating fingers causing them to bend (when voltage is applied) toward the electrodes, thus causing a change in the distance from grating to reflective membrane. This change in distance causes a change in the interference pattern produced, which can be advantageous if the electrostatic actuation is performed in a controlled manner. The controller can be configured to apply the electrical signals to perform the electrostatic actuation. The controller may be coupled to the processor to form a feedback loop. In this manner, the position of the grating can be varied such that the device is calibrated to measure at optimal sensitivity. Furthermore, by utilizing a modulation signal which can be applied to the electrodes and grating, and utilizing commonly known frequency lock-in methods noise can be filtered out, thus increasing the SNR of the device.

FIG. 5 is a diagram illustrating another embodiment of a micro-displacement measurement device in accordance
with embodiments of the present disclosure. The device includes a light source 240 and a photo-diode 220 on the surface of an opaque, rigid substrate 260. An optical diffraction grating 215 exists above the light source 240 and is characterized by alternating regions of reflective and transparent passages 217. A backside cavity 280 formed between the grating 215 and the substrate 260 may be sealed at some desired pressure (including low pressures) with any gas or gas mixture, or can be open to ambient through an opening with desired flow resistance. Finally a reflective membrane 250 exists above the diffraction grating 215 that reflects light back towards the substrate 260. The diffraction grating 215 and the reflective membrane 250 together form a phase-sensitive diffraction grating.

The diffraction grating 215 is formed on a silicon substrate by first depositing an oxide layer followed by the deposition and patterning of a conductive and reflective thin film such as polysilicon in the form of a grating. A silicon nitride layer deposition is used to encapsulate the grating fingers and then patterned to expose the underlying oxide between the grating fingers. The grating is released by first etching the bulk silicon using a deep reactive ion etching which stops at the oxide layer. This is followed by wet etching of the oxide between the grating fingers hence providing free space optical access to the reflective top membrane.

The reflective membrane 250 is suspended in a bridge-like structure and may be composed of a non-conductive material, such as a stretched polymer membrane, polysilicon, silicon-nitride, or silicon-carbide, and then making the material conductive in a desired region either through depositing and patterning a conductive material such as aluminum, silver, or any metal. Alternatively, the non-conductive material may be doped with a conductive material. The reflective membrane 250 can also be coated with a reflective material, which makes aluminum or silver a good choice. In some applications such as chemical and biological sensors, the reflective membrane 250 can be made of a single material or a multi-layered material that changes its optical properties, such as reflectivity in response to a chemical or biological agent for example a polymer film dissolving in a solvent. Similarly, the reflective membrane 250 can be a micromachined cantilever made of single or layered material that deforms, or moves, due to thermal, chemical, or other physical stimulus. For example, the device 200 can be configured to be an infrared (IR) sensor by having a bimorph structure as the reflective membrane 250 that includes an IR absorbing outer layer and a reflective layer facing the light source 240. In some other applications, such as a microphone or a pressure sensor, the reflective membrane 250 can be in the shape of a diaphragm.

A gap 285 is formed between the rigid structure 210 and the reflective membrane 250. The gap 285 should be large enough to have at least one optimal detection sensitivity point, i.e., highest slope of the curves 32, 34 and smaller than half the coherence length of the light source.

The backside cavity 280 is used to adjust the effect of air on the mechanical response of the membrane 250. If the cavity 280 is very small, the spring-like stiffness of the air will be high as compared to the membrane stiffness and hence dominate the overall mechanical response. Utilizing a large cavity, e.g., 500x500x500 μm³, the air stiffness can be reduced to negligible levels. Another function of the backside cavity 280 is to provide optical access and longitudinal distance for the separation of diffraction orders for detection by photo-detectors 220.

A controller 270 may be coupled to the reflective membrane 250 and the rigid structure 210 so as to apply a voltage bias to electrostatically actuate the reflective membrane 250.

When a controlled voltage bias is applied, various aspects of the reflective membrane 250 can be altered. First, the position, with respect to the diffraction grating 215 can be changed. Secondly the rigidity of the reflective membrane 250 may be altered. In many applications, moving or controlling the position of the reflective membrane 250 will be desired for self-calibration, sensitivity optimization, and signal modulation purposes. For example, if the reflective membrane 250 is a diaphragm as in the case of a microphone or a capacitive micromachined transducer, vibrating the diaphragm to produce sound in a surrounding fluid may be desired for transmission and self-calibration. Also, while measuring the displacement of the diaphragm, controlling the nominal gap height to a position that will result in maximum possible sensitivity for the measurement may be desired.

The substrate 260 may be a printed circuit board, a silicon wafer, or any other solid material. Furthermore, the light source 240 and photo-diode 220 may be constructed or sourced externally and attached to the surface or fabricated directly into the material using integrated circuit or micromanufacturing techniques.

The light source 240 can be an optical fiber or end of a microfabricated waveguide with an appropriate reflector to direct the light to the desired location in the device 200. The light source 140 of the embodiment illustrated in FIG. 4 is similar to the light source 240 here. Likewise, the photo-diode 220 serves as a specific example of a photo-detector, as discussed in relation to FIG. 4.

The operation of the device 200 is fairly similar to that of device 100. An incident light beam 201 is illuminated upon the diffraction grating 215, where in turn a first portion of the light is reflected back towards the substrate 260. A second portion of the light is diffracted about the diffraction grating 215 and reflected off of the reflective membrane 250 back toward the substrate 260. An interference pattern of the two reflective portions is formed. A photo-diode 220 is positioned to receive, in this embodiment, the first order of the interference pattern. Various functions can alter the reflective membrane 250, thus changing the interference pattern. First, the distance of the reflective membrane 250 relative to the diffraction grating 215 (the gap 285 height) can change due to a number of reasons. One reason is due to a number of external excitations, such as acoustic pressure causing the membrane 250 to vibrate at a particular frequency. Another external excitation may be because of a chemical reaction occurring on the membrane 250, such as change in the residual stress in a composite membrane due to dissolution of one of the layers. A third external excitation may be an infrared light source illuminated upon the membrane 250, causing the membrane 250 to change position. There are a great number of possibilities that can alter the position of the reflective membrane 250, all of which are too many to list here. The controller 270 can also be factored into the movement of the reflective membrane 250 either in a modulated approach or a static approach.

Second, the reflectivity of the membrane 250 may be altered, such that the power level of the second portion of the reflected light is altered. This change in the power level can be detected by the photo-diode 220. The reflectivity of the membrane 250 may be altered by a chemical or biological reaction. Examples of these reactions can be those causing a color change or change in membrane thickness. It is well known that the reflectivity of thin films strongly depends on thickness. Therefore corrosion, etching, or deposition of different materials on the membrane 250 due to chemical or biological processes will alter the reflected light.

Third, the rigidity of the membrane 250, and thus the magnitude in which the membrane 250 will vibrate can be
altered in time and measured by the photo-diode 220. The rigidity of the membrane 250 may be a factor of an external force, but more than likely will be caused by an electrostatic charge applied by the controller 270. Varying the rigidity of the membrane 250 provides for another possibility. That is to vary the rigidity of the membrane 250 as a function of the acoustic pressure applied to the membrane 250. The attempt would be to keep the membrane 250 as still as possible. With this approach, one can measure the varying voltage needed to accomplish this, and thus be using a force-feedback approach to measure the applied acoustic pressure. Force-feedback is a well known method in the art that can typically produce more accurate and sensitive results. The device 200 can be made at such a small scale, that it is very practical to string together these devices in an array or matrix structure. Being able to build microphone arrays on a single substrate over a small surface area allows fabrication of devices with closely matched responses. By measuring the acoustic pressure using several closely spaced, matched microphone array elements the pressure gradients may be measured accurately to implement acoustic intensity probes. Furthermore, some signal processing methods such as gradient flow algorithms results in significant noise reduction using a two-dimensional array of microphone arrays with a periodicity much smaller than the acoustic wavelength. The embodiments of the present disclosure enable implementation of such closely spaced microphones without loss of signal fidelity.

FIG. 6 illustrates some variations to the embodiment illustrated in FIG. 5. First, an air release channel 382 could be implemented in either of the devices 200 or 300. The air release channel 382 serves to equalize the pressure inside the cavity 380 with the ambient pressure preventing the collapse of the microphone membrane 350 in response to changing ambient pressure which can be due to wind or other non-acoustic changes in atmospheric pressure.

Secondly, a second diffraction grating 355 can be deposited on a transparent membrane 350 rather than a membrane with a mirror-like uniform reflective surface as in the previous embodiments. The grating 355 on the membrane 350 has the same periodicity as the first, the reference, diffraction grating 315, but is offset and has diffraction grating fingers whose width is smaller than the gap between the fingers of the reference diffraction grating 315. This structure allows some of the incident light to transmit through the whole device 300 and also introduces new diffraction orders in the reflected field. This produces a new kind of phase grating.

To understand the operation one can consider the phase of the light reflected from the reference grating (\( \phi_1 \)) and the grating on the membrane (\( \phi_2 \)). When the difference between \( \phi_1 \) and \( \phi_2 \) is \( 2k\pi, k=0, 2, 4, \ldots \), the apparent period of the grating is \( \Lambda_1 \) (apparent reflectivity of 1, 0, 1, 0 regions assuming perfect transmission through the transparent membrane 350) and the even diffraction orders are reflected with angles

\[
\sin(\theta_n) = \frac{n\lambda}{\Lambda_1}, \quad n = 0, \pm 2, \pm 4, \ldots
\]

In contrast, when the difference between \( \phi_1 \) and \( \phi_2 \) is \( m\pi, m=-1, 3, 5, \ldots \), the apparent period of the grating is \( 2\Lambda_2 \) (apparent reflectivity of 1, 0, -1, 0, 1 regions assuming perfect transmission through the transparent membrane 350) and the odd diffraction orders are reflected with angles

\[
\sin(\theta_n) = \frac{n\lambda}{2\Lambda_2}, \quad n = 1, \pm 3, \pm 5, \ldots
\]

Here it is assumed that the width of the reflective grating fingers on the reference grating 315 and the grating 355 on the membrane 350 are the same. This does not have to be the case if the interfering beams go through different paths and experience losses due to reflection at various interfaces and also incidence angle variations. The diffraction grating geometry can then be adjusted to equalize the reflected order intensities with optimized interference.

Note that in this embodiment, the intensity of the odd and even numbered orders change with 180° out of phase with each other when the gap between the reference and sensing diffraction grating changes. The even numbered diffraction orders are in phase with the zero order reflection. The advantage of having other off-axis even diffraction orders in phase with the specular reflection is that it enables one to easily use differential techniques. This is achieved by taking the difference of the outputs of two detectors (i.e., photo-diodes 320 and 322) to detect odd and even orders, respectively. Hence, the common part of the laser intensity noise which is common on both orders can be eliminated.

Similar electrostatic actuation techniques can be applied by the controller 370. Furthermore, similar to the device 200 of FIG. 5, the device 300 can be fabricated at such a small scale that it is very feasible to arrange many devices 300 in an array or matrix structure.

FIG. 7 illustrates yet another embodiment of the present disclosure. In this embodiment, a reflective diffraction grating 455 is located on a transparent membrane 450. A platform 410 includes a reflective surface, and the device 400 forms a phase sensitive diffraction grating when illuminated from the bottomside of the membrane 450 with an incident light beam 401. The zero and all odd orders are reflected back and have intensities that depend on the distance between the grazing 455 and the platform 410. Note that this gap includes the thickness of the membrane 450, which may be made of any transparent material. Examples include silicon dioxide, silicon nitride, quartz, sapphire, or a stretched polymer membrane such as parylene.

Since the only potential requirement of the platform 410 is to be reflective, any material including semiconductor substrates or plastics can suffice given that they are coated with a reflective layer, such as metal. To add the electrostatic actuation feature, a region of both the platform 410 and the membrane 450 can be made electrically conductive. For the membrane 450, this can be accomplished by using a material that is both reflective and conductive for the diffraction grating 455.

This particular embodiment offers remote sensing capabilities, as the light source, as well as any photo-detectors, may be located remote from the device 400. For example, if measuring the displacement of the membrane 450 due to a change in pressure is desired (as would be the case for a pressure sensor or a microphone), the platform 410 can be attached to a surface and the light source and detectors can be stationed in a remote location not necessarily close to the membrane 450.

In addition to remote measurements, this device 400 can be remotely actuated to modulate the output signal. For example, an acoustic signal at a desired frequency can be directed to the membrane 450 and the output signal can be measured at the same frequency using a method such as a lock-in amplifier.
The magnitude and phase of the output signal would give information on the location of the membrane 450 on the optical intensity curve of FIG. 3, which in turn may depend on static pressure, and other parameters such as temperature, etc. Similar modulations techniques can be implemented using electromagnetic radiation, where an electrostatically biased membrane 450 with fixed charges on it can be moved by applying electromagnetic forces. In this case, the membrane 450 would be made with a dielectric material with low charge leakage.

FIG. 8 is a flow chart illustrating a method 800 for optimizing the sensitivity of a micro-displacement measurement device and more generally improving the overall performance of a device in accordance with embodiments of the present disclosure.

The method 800 begins with measuring the distance d (block 805). Once the distance is measured by the device, the measurement data can be processed so that the distance can be calculated (block 840). Typically, this can be performed by a processor, which may be a computing device such as a personal computer. The processor may be configured to perform several other functions with the data as well.

Either before or after the data is calculated, a control signal may be generated based on the measured and/or calculated data to actuate fingers of a tunable diffraction grating of the device (block 850) or actuate the reflective membrane. Once the device has been appropriately actuated, the measurements may be made again. This procedure may continue, as the feedback loop provides for constant monitoring.

As described in sufficient detail in prior figures, several embodiments of devices can properly measure the distance, and the change of d in time. A simplified description of the general method of measuring the distance may begin with illuminating the reflective membrane with an incident light beam through the tunable diffraction grating (block 810). Once illuminated, interference patterns can develop through constructive and destructive interference of reflected light off of the tunable diffraction grating and reflections off of the membrane that has been diffracted through the diffraction grating. A photo-detector may then receive the interference pattern (block 820). Once received proper electrical components working with the photo-detector or included within the photo-detector may then measure the intensity of light of the interference patterns (block 830). Interpretation of the interference patterns may come in subsequent calculations.

From either the measured intensity of the interference patterns or from processed calculations, a voltage potential may be generated that carries proper actuation information. The voltage potential may carry a DC portion that can deform the membrane 450 with fixed charges on it can be moved by applying electromagnetic forces. In this case, the membrane 450 would be made with a dielectric material with low charge leakage.

According to some embodiments of the disclosed devices, the sensor structure can be modified to enhance desired performance characteristics. For example, the mechanical sensitivity for the disclosed sensor structures can be defined as the maximum displacement of the membrane for a given pressure. The membranes described thus far have generally been described as being uniform in thickness, and the membranes deflect into a concave shape when a net pressure is applied on the top side of the membrane. Thus, such maximum displacement can be measured, for example, from the center of the concave membrane displacement. Since the membrane displacement is detected optically for such devices, it can be desirable to have as flat a deflection profile as possible, while still maintaining good mechanical sensitivity. Said another way, it can be desirable for the reflective surface of the membrane to be flat, even during the deflection of the membrane.

According to one embodiment, a sensitivity increase can be achieved using an increased gap thickness to provide an air-sealed cavity having a volume larger than devices having relatively smaller gap thicknesses. For example, with reference to FIG. 9, a sensor 900 is disclosed having such an increased gap height to reduce the stiffness of trapped air within the cavity, thereby increasing the mechanical sensitivity of the membrane.

More specifically, FIG. 9 illustrates a device having similar operating principles of the sensor structures of the previously described microphones. Similar to the devices of FIGS. 1 and 2, for example, device 900 includes a target surface 902 (which may be a reflective surface of a mechanical structure 904, such as a beam or flexible membrane) placed a distance 906 away from a reference point. In this case, the reference point is a reflective diffraction grating 908 formed on transparent substrate 910.

When air is trapped in the membrane-substrate gap a substantially air-tight sealed cavity 912 is formed. However, a reduction in mechanical sensitivity may occur due to the added stiffness caused by the compression (or vacuum) of trapped air when the membrane is deflected. Therefore, additional enhancements in mechanical sensitivity can be made by reducing this effect.

The stiffness due to the air is inversely proportional to the volume of the cavity 912. Thus, the stiffness can be reduced by increasing the gap height appropriately (i.e. distance 906). The sensitivity of the optical detection method is not adversely affected by large gap heights, so long as the coherence length requirement of the light source is met. Thus, distance 906 can be a relatively large distance in comparison to the gap thicknesses described in other embodiments such that the volume of air in cavity 912 is increased to effectively increase the sensitivity of the device.

However, the disclosed device embodiments that are configured to electrostatically actuate the membrane may not operate as effectively with a larger gap height. That is, the electrostatic actuation force used to move the membrane is inversely proportional to the gap height squared. Thus, according to some embodiments, tall electrodes 914 can be placed at the outer regions of the structure 902. Using such a configuration, the membrane displacement can still be detected optically while the tall side electrodes are manufactured to be tall enough, or otherwise positioned, such that they are close to the membrane to enable the electrostatic actuation of the membrane. Such electrostatic actuation can be controlled by a controller 916, for example. Some embodiments of device 900 could include a controller for providing an electrical bias to the reflective diffraction grating 908 as described in previous embodiments. Such embodiments hav-
At least the following is claimed:

1. A fabricated device comprising: a phase-sensitive reflective diffraction grating for reflecting a first portion of an incident light and transmitting a second portion of the incident light such that the second portion of the incident light is diffracted; a mechanical structure having a first region and a second region, the mechanical structure positioned a distance \( d \) above the diffraction grating and forming a wall of a cavity, the second portion of the incident light is reflected off of the first region of the structure such that an interference pattern is formed by the reflected first portion and the reflected second portion of the incident light; and

an orifice formed in the mechanical structure to provide for the passage of air between the inside and outside of the cavity.

2. The fabricated device of claim 1, wherein the orifice is formed in the second region of the mechanical structure.

3. The fabricated device of claim 1, wherein the cavity includes:

   a side wall for positioning the mechanical structure at the distance \( d \) from the diffraction grating, the side wall comprising the orifice.

4. The fabricated device of claim 3, wherein another orifice for the passage of air between the inside and outside of the cavity is formed in the mechanical structure.

5. The fabricated device of claim 4, wherein the orifice is formed in the second region of the mechanical structure.

6. The fabricated device of claim 3, wherein the orifice is formed in an outer region of the sidewall.

7. The fabricated device of claim 3, wherein the orifice is formed in an outer region of the sidewall.

8. The fabricated device of claim 1, wherein the orifice is formed in the second region of the mechanical structure.

9. The fabricated device of claim 1, further comprising:

   a substrate forming a wall of the cavity, and the orifice is formed in the substrate.

10. The fabricated device of claim 9, wherein the orifice formed in the substrate is not in the path of incident light directed through the substrate and toward the reflective diffraction grating.

11. The fabricated device of claim 1, further comprising:

    a controller coupled to said reflective diffraction grating for controllably adjusting at least a first feature of said reflective diffraction grating.

12. The fabricated device of claim 11, wherein said controller controllably adjusts the distance \( d \) between the diffraction grating and the mechanical structure.

13. The fabricated device of claim 1, wherein the orifice is formed during fabrication of the mechanical structure.

14. The fabricated device of claim 13, wherein the mechanical structure is microfabricated.

15. The fabricated device of claim 14, wherein the mechanical structure is formed by chemical etching.

16. The fabricated device of claim 1, wherein the orifice is formed in an outer region of the mechanical structure.

17. A device comprising:

   means for equilizing the air pressure between an inside and outside of a cavity, the cavity including a wall comprising a mechanical structure having a first region and a second region;

   means for illuminating a reflective diffraction grating with an incident light, the diffraction grating being positioned a distance \( d \) from the mechanical structure, a first portion of the incident light being reflected and a second portion
of the incident light transmitted through the diffraction grating such that the second portion of the incident light is diffracted; and
means for reflecting the second portion of the incident light off of the first region of the mechanical structure such that an interference pattern is formed by the reflected first portion and the reflected second portion of the incident light,
wherein the means for equalizing the air pressure comprises means for venting the air through an orifice formed in the mechanical structure.

18. The device of claim 17, wherein the means for equalizing the air pressure further comprises means for venting the air through an orifice in at least one wall of the cavity.

19. The device of claim 17, wherein the means for venting the air through the orifice includes means for venting the air through an orifice formed in the second portion of the mechanical structure.

20. The device of claim 17, wherein the means for venting the air through the orifice includes means for venting the air through an orifice formed in a side wall of the cavity, the side wall for positioning the mechanical structure at a distance from the diffraction grating.

21. The device of claim 17, wherein the means for venting the air through the orifice includes means for venting the air through an orifice formed in a substrate, the substrate forming a wall of the cavity.

22. A microfabricated microphone comprising:
- a phase-sensitive reflective diffraction grating for reflecting a first portion of an incident light and transmitting a second portion of the incident light such that the second portion of the incident light is diffracted;
- a substrate positioned below the diffraction grating;
- a diaphragm positioned a distance above the diffraction grating such that the second portion of the incident light is reflected off the structure to form an interference pattern by the reflected first portion and the reflected second portion of the incident light, the diaphragm including a sidewall adjoining the substrate such that the diaphragm and the substrate enclose a cavity; and
- an orifice formed in the diaphragm to provide for the passage of air between the inside and outside of the cavity.

23. The microfabricated microphone of claim 22, wherein the orifice is formed during fabrication of the diaphragm.

24. The microfabricated microphone of claim 23, wherein the diaphragm is formed by chemical etching.

25. The microfabricated microphone of claim 22, wherein the orifice is formed in an outer region of the diaphragm.

26. The microfabricated microphone of claim 22, further comprising:
- a controller coupled to the reflective diffraction grating for controllably adjusting at least a first feature of said reflective diffraction grating.

27. The microfabricated microphone of claim 26, wherein said controller controllably adjusts the distance between the diffraction grating and the mechanical structure.
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 20, line 29, the word “granting” should be read --grating--.

Signed and Sealed this
Thirtieth Day of June, 2009

[Signature]

JOHN DOLL
Acting Director of the United States Patent and Trademark Office