(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
22 October 2020 (22.10.2020)

WIPO | PCT

(10) International Publication Number
WO 2020/212878 A1

(51) International Patent Classification:
G01L 9/00 (2006.01) *G01L 21/22* (2006.01)

(21) International Application Number:
PCT/IB2020/053571

(22) International Filing Date:
15 April 2020 (15.04.2020)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/835,757 18 April 2019 (18.04.2019) US

(71) Applicant: **KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY** [SA/SA]; 4700 King Abdullah University of Science and Technology, Thuwal 23955-6900 (SA).

(72) Inventors: **ALCHEIKH, Nouha**; 4700 King Abdullah University of Science and Technology, Thuwal 23955-6900 (SA). **HAJJAJ, Amal**; 4700 King Abdullah University of Science and Technology, Thuwal 23955-6900 (SA). **YOUNIS, Mohammad Ibrahim**; 4700 King Abdullah University of Science and Technology, Thuwal 23955-6900 (SA).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,

(54) Title: WIDE RANGE HIGHLY SENSITIVE PRESSURE SENSOR BASED ON HEATED MICROMACHINED ARCH BEAM

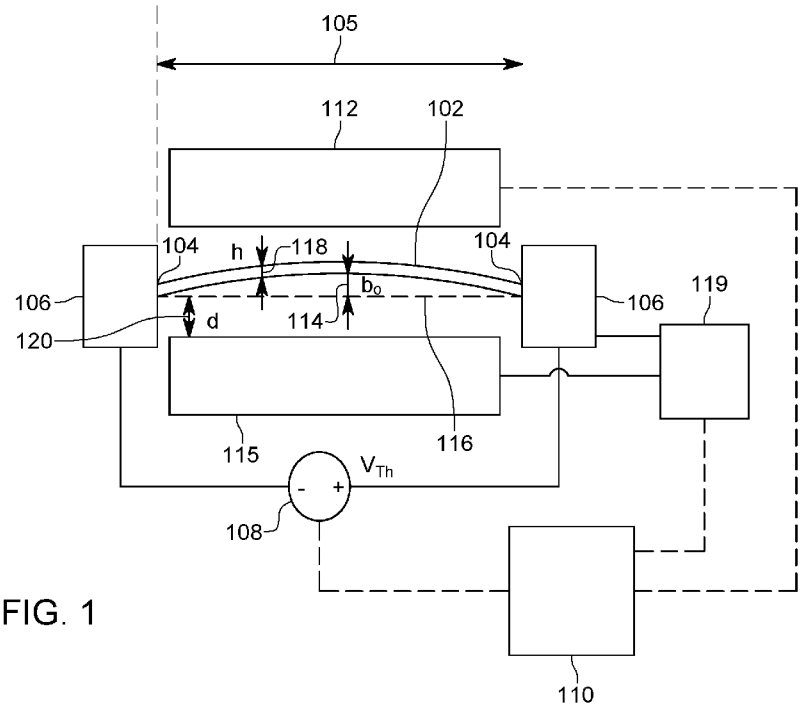


FIG. 1

(57) Abstract: A device for measuring pressure includes a curved microbeam having opposing ends, a length extending between the pair of opposing ends, and a plurality of resonant frequencies, an actuating electrode extending along the length of the curved microbeam and spaced from the curved microbeam, an AC power source in communication with one of the opposing ends and the actuating electrode to deliver an AC signal at a first symmetric resonant frequency and a second symmetric resonant frequency selected from the plurality of resonant frequencies to the curved microbeam, a DC power source in communication with the opposing ends to pass an electrothermal voltage along a length of the curved microbeam, and a frequency monitoring device to monitor changes in the first symmetric resonant frequency and the second symmetric resonant frequency caused by an ambient pressure surrounding the curved microbeam.

WO 2020/212878 A1

[Continued on next page]

SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *of inventorship (Rule 4.17(iv))*

Published:

— *with international search report (Art. 21(3))*

WIDE RANGE HIGHLY SENSITIVE PRESSURE SENSOR BASED ON HEATED MICROMACHINED ARCH BEAM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 62/835,757, filed on April 18, 2019, entitled "WIDE RANGE HIGHLY SENSITIVE PRESSURE SENSOR BASED ON HEATED MICROMACHINED ARCH BEAM," the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

TECHNICAL FIELD

[0002] Embodiments of the subject matter disclosed herein generally relate to pressure sensors and pressure microsensors.

DISCUSSION OF THE BACKGROUND

[0003] In recent years, miniaturized vacuum pressure sensors have received increasing attention, in addition to other environmental sensors, such as temperature, flow, gas, and mass sensors. Pressure micro-sensors have been explored for applications, such as industrial control, healthcare, medical testing, aerospace, meteorology, and environmental monitoring. Different sensing mechanisms and arrangements have been used for the detection of air-pressure, for example, capacitive, piezoelectric, piezoresistive, and resonant. Resonant pressure

micro-sensors have the advantage of digital frequency output, which can be measured with high precision using simple electronic circuits. Their principle of operation of resonant pressure micro-sensors is based on tracking the resonant frequency shift caused by the change of internal stress due to the change of the surrounding air pressure. Compared to other sensing mechanisms, tracking the resonant frequency shift yields high accuracy, high stability, high sensitivity, and better immunity to noise.

[0004] The resonant frequency tuning of silicon resonators can be achieved by electrostatic, magnetic, thermal, or electrothermal excitation. Despite the higher power consumption, electrothermal excitation is a more robust technique and requires low actuation voltages. In addition, electrothermal excitation is simpler in fabrication compared to other methods. A previous sensitive pressure-sensor based on the convective cooling of an electrothermally heated resonant straight micro-beam utilized the fundamental mode operated near the buckling point. Sensitivity up to 77,081 ppm/Torr ($77{,}081 \times 10^{-6}$/Torr) was demonstrated for a pressure range from 1 to 10 Torr. To alleviate the dip in frequency near the buckling instability, a pressure-sensor was demonstrated using an initially curved arch micro-beam. That pressure-sensor showed a sensitivity of 10,482 ppm/Torr.

[0005] Previous arrangements of pressure-sensors, however, were limited to a narrow range of pressures. Thus, there is a need for a pressure sensing device with enhanced sensitivity and wide pressure range, which is also simple in fabrication, operation, and sensing scheme.

BRIEF SUMMARY OF THE INVENTION

[0006] According to an embodiment, a pressure sensor uses an electrothermally heated initially curved micro-beam exhibiting the veering phenomenon among its first two symmetric vibration modes. The pressure sensor offers more continuity in frequency variations and thus high sensitivity in wide range of pressure.

[0007] According to another embodiment, there is a method for sensing pressure by electrothermally heating a curved microbeam having a plurality of resonant frequencies, electrostatically driving the curved microbeam at a first symmetric resonant frequency and a second symmetric resonant frequency selected from the plurality of resonant frequencies, monitoring changes in the first symmetric resonant frequency and the second symmetric resonant frequency caused by an ambient pressure surrounding the curved microbeam and using the monitored changes in the first symmetric resonant frequency and the second symmetric resonant frequency to determine the ambient pressure.

[0008] In one embodiment, an electrothermal voltage is passed along a length of the curved microbeam to heat the curved microbeam electrothermally. A suitable electrothermal voltage is 4 VDC. In one embodiment, the electrothermal voltage is selected to cause a maximum displacement at a midpoint along the length of the curved microbeam of less than 12μm and a temperature within the curved microbeam below a curved microbeam melting point.

[0009] In one embodiment, the first symmetric resonant frequency is associated with a first symmetric vibration mode, and the second symmetric resonant frequency is associated with a second symmetric vibration mode. In one embodiment, the first symmetric vibration mode is a fundamental vibration mode, and the second symmetric vibration mode is a third vibration mode. In one embodiment, an AC power source in communication with the curved microbeam and an actuating electrode to deliver an AC signal to the curved microbeam to drive the curved microbeam electrostatically. The actuating electrode extends along a length of the curved microbeam and is spaced from the curved microbeam. In one embodiment, the actuating electrode is spaced from the curved microbeam by a distance of at least 12μm.

[0010] In one embodiment, monitoring changes in the first symmetric resonant frequency and the second symmetric resonant frequency includes monitoring changes in the second symmetric resonant frequency when increases in the ambient pressure cause decreases in the second symmetric resonant frequency and monitoring changes in the first symmetric resonant frequency when increases in the ambient pressure cause increases in the second symmetric resonant frequency.

[0011] In one embodiment, the curved microbeam is selected to have dimensions and an initial rise at a midpoint along a length of the curved microbeam that produce strong veering between a plot of changes in the first symmetric resonant frequency with ambient pressure and changes in the second symmetric resonant frequency with ambient pressure. In one embodiment, a curved microbeam is selected wherein the length is 800 μm, and the initial rise at the midpoint along the

length is 2.6 μm. In addition, the curved microbeam has a width perpendicular to the length of 25 μm and a thickness perpendicular to the length and parallel to the initial rise of 1.5 μm.

[0012] According to another embodiment, there is a resonant pressure sensor containing a curved microbeam with a pair of opposing ends, a length extending between the pair of opposing ends, and a plurality of resonant frequencies, an actuating electrode extending along the length of the curved microbeam and spaced from the curved microbeam, an AC power source in communication with one of the opposing ends and the actuating electrode to deliver an AC signal at a first symmetric resonant frequency and a second symmetric resonant frequency selected from the plurality of resonant frequencies to the curved microbeam, a DC power source in communication with the opposing ends to pass an electrothermal voltage along a length of the curved microbeam, a frequency monitoring device to monitor changes in the first symmetric resonant frequency and the second symmetric resonant frequency caused by an ambient pressure surrounding the curved microbeam.

[0013] In one embodiment, the curved microbeam has dimensions and an initial rise from the opposing ends at a midpoint along the length of the curved microbeam that produce strong veering between a plot of changes in the first symmetric resonant frequency with ambient pressure and changes in the second symmetric resonant frequency with the ambient pressure. In one embodiment, the length is 800 μm, and the initial rise at the midpoint along the length is 2.6 μm. In

addition, the curved microbeam has a width perpendicular to the length of 25 μm and a thickness perpendicular to the length and parallel to the initial rise of 1.5 μm.

[0014] In one embodiment, the actuating electrode is spaced from the curved microbeam by a distance of at least 12μm at the opposing ends of the curved microbeam. In one embodiment, the first symmetric resonant frequency is associated with a first symmetric vibration mode, and the second symmetric resonant frequency is associated with a second symmetric vibration mode. In one embodiment, the first symmetric vibration mode is a fundamental vibration mode, and the second symmetric vibration mode is a third vibration mode. In one embodiment, the electrothermal voltage comprises 4 VDC. In one embodiment, the electrothermal voltage causes a maximum displacement at a midpoint along the length of the curved microbeam between the opposing ends of less than 12μm and a temperature within the curved microbeam below a curved microbeam melting point. In one embodiment, the frequency monitoring device comprises a laser Doppler vibrometer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0016] Fig. 1 is a schematic representation of an embodiment of a resonant pressure sensor;

[0017] Fig. 2 is a graph of frequency versus axial load that illustrates operation of the resonant pressure sensor using an electrothermally heated clamped-clamped curved microbeam;

[0018] Fig. 3 is a flow chart illustrating and embodiment of a method for measuring pressure using a resonant pressure sensor;

[0019] Fig. 4 is a schematic representation of an experimental setup for testing the resonant pressure sensor;

[0020] Fig. 5 is a graph illustrating experimental data and finite element simulations of the first two symmetric resonant frequencies of the curved microbeam while varying the electrothermal voltage at 38 mTorr pressure;

[0021] Fig. 6 is a graph illustrating experimental data and finite element simulations of the first two symmetric resonant frequencies of the curved microbeam while varying the electrothermal voltage at atmospheric pressure;

[0022] Fig. 7 is a graph illustrating the measured percentage relative shift of the resonant frequency with pressure for an electrothermal voltage of 4 V;

[0023] Fig. 8 is a graph illustrating finite element simulations of the percentage relative shift of resonant frequency and the sensitivity with pressure at an electrothermal voltage of 4 V;

[0024] Fig. 9 is a graph illustrating finite element simulations of the percentage relative shift of resonant frequency and the sensitivity with pressure at an electrothermal voltage of 8.5 V;

[0025] Fig. 10 is a graph illustrating finite element simulations of the sensitivity with pressure an electrothermal voltage of 4 V at different thickness values for the microbeam; and

[0026] Fig. 11 is a graph illustrating finite element simulations of the sensitivity with pressure an electrothermal voltage of 4 V at different air volume surrounding the micro-beam.

DETAILED DESCRIPTION OF THE INVENTION

[0027] The following description of the embodiments refers to the accompanying drawings. The same reference numbers in different drawings identify the same or similar elements. The following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims. The following embodiments are discussed, for simplicity, with regard to a resonant pressure sensor. However, the embodiments to be discussed next are not limited to a single resonant pressure sensor, but may be applied to plural resonant pressure sensors.

[0028] Reference throughout the specification to "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with an embodiment is included in at least one embodiment of the subject matter disclosed. Thus, the appearance of the phrases "in one embodiment" or "in an embodiment" in various places throughout the specification is not necessarily referring to the same embodiment. Further, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

[0029] Referring initially to Fig. 1, exemplary embodiments are directed to a resonant pressure sensor 100. The resonant pressure sensor includes an arched or curved microbeam 102. Suitable materials for the curved microbeam include, but are not limited to, silicon, gold, etc. In one embodiment, the resonant pressure sensor containing the arched or curved microbeam resonator is fabricated from Silicon-On-Insulator Multi User MEMS Processes (SOIMUMPs).

[0030] The curved microbeam 102 includes a pair of opposing ends 104 and a length 105 extending between the pair of opposing ends. The opposing ends are secured in mounting or clamping structures 106. In one embodiment, the clamping structures are constructed of a conductive material to communicate DC and AC currents to the curved microbeam. Therefore, the opposing ends are fixed, and the curved microbeam exhibits a plurality of resonant frequencies. The curved microbeam includes symmetric resonant frequencies associated with symmetric vibration modes. Exemplary embodiments utilize two symmetric resonant frequencies, e.g., a first symmetric resonant frequency and a second symmetric resonant frequency, to drive the curved microbeam electrostatically. The selected resonant frequencies are selected from the plurality of resonant frequencies associated with the curved microbeam. In one embodiment, the first symmetric resonant frequency is associated with a first symmetric vibration mode and the second symmetric resonant frequency is associated with a second symmetric vibration mode. In one embodiment, the first symmetric vibration mode is a fundamental vibration mode of the curved microbeam, and the second symmetric vibration mode is a third vibration mode of the curved microbeam.

[0031] Referring now to Fig. 2, the second symmetric resonant frequency of the second symmetric vibration mode 202, e.g., the third vibration mode, is monitored while the curved microbeam is actuated with an electrothermal voltage 204, V_{Th}. As the pressure applied to the curved microbeam 102, i.e., the ambient pressure, increases, the axial load 206 of the curved microbeam decreases due to the cooling effect of the surrounding air. Therefore, the second symmetric resonant

frequency decreases until reaching the veering zone 208, i.e., the transition point 210. After the transition point 210, the frequency tracking switches to the first symmetric resonant frequency 212, e.g., the fundamental resonant frequency. When using the resonant pressure sensor 100 to determine the ambient pressure, changes in the second symmetric resonant frequency are monitored when increases in the ambient pressure cause decreases in the second symmetric resonant frequency, and changes in the first symmetric resonant frequency are monitored when increases in the ambient pressure cause increases in the second symmetric resonant frequency. The inset 214 shows an image of scanning electron microscopic (SEM) used for measurements of the fabricated curved micro-beam resonator.

[0032] As illustrated in Fig. 2, monitoring between the first and second symmetric resonant frequencies changes or switches on either side of the veering zone. The plots of the first and second symmetric resonant frequencies do not cross, by get very close to each other at the transition point before veering away from each other. The smaller the distance between the plots of the first and second symmetric resonant frequencies at the transition point, the stronger the veering, which is preferred.

[0033] Returning to Fig. 1, the curved microbeam 102 has an initial rise 114, b_0, from the opposing ends or from the straight level 116 at a midpoint along the length 105 of the curved microbeam that produce strong veering between the plot (Fig. 2) of changes in the first symmetric resonant frequency with ambient pressure and changes in the second symmetric resonant frequency with ambient pressure. In one embodiment, the curved microbeam has a length 105 of 800 μm, an initial rise at

the midpoint along the length of 2.6 μm, a width perpendicular to the length of 25 μm, and a thickness 118, h, perpendicular to the length and parallel to the initial rise of 1.5 μm. One skilled in the art would understand that variations of these dimensions about +/- 20% would also achieve some of the advantages of this embodiment. Exemplary embodiments of the pressure resonant sensor provide simplicity in fabrication with low-cost and size scalability.

[0034] The resonant pressure sensor includes an actuating electrode 115 extending along the length of the curved microbeam 102 to apply VDC and AC actuation between the actuating electrode and the curved microbeam. The actuating electrode is spaced from the curved microbeam by a given distance 120, d. In one embodiment, the given distance is the transduction gap between the actuated electrode and the clamped ends of the curved microbeam. As the curved microbeam curves away from the actuating electrode, the activating electrode is spaced from the curved microbeam at least by the given distance. In one embodiment, the given distance is 12μm. In one embodiment, the given distance is greater than 12μm. In one embodiment, the given distance is less than 8μm. In general, using a higher gap helps the beam to deflect with high displacement while actuated with electrothermal voltage and low pressure.

[0035] The resonant pressure sensor includes an AC power source 119 in communication with one of the opposing ends and the actuating electrode to deliver an AC signal at both the first symmetric resonant frequency and the second symmetric resonant frequency. Suitable AC power sources include, but are not limited to, amplifiers. In one embodiment, the AC power source is in communication

with the clamping mechanism holding one of the opposing ends. In one embodiment, the first symmetric resonant frequency is associated with a first symmetric vibration mode, and the second symmetric resonant frequency is associated with a second symmetric vibration mode. In one embodiment, the first symmetric vibration mode is a fundamental vibration mode, and the second symmetric vibration mode is a third vibration mode.

[0036] The resonant pressure sensor includes a DC power source 108 in communication with the opposing ends to pass an electrothermal voltage along a length of the curved microbeam. In one embodiment, the DC power source is in communication with the clamping mechanisms holding the opposing ends. The electrothermal voltage is selected to cause a desired maximum rise 114 at a midpoint along the length of the curved microbeam between the opposing ends. In one embodiment, the maximum rise is less than 12μm. The electrothermal voltage increases the temperature within the curved microbeam. In one embodiment, the electrothermal voltage is selected to ensure that the temperature of the curved beam stays below the curved beam melting point, which for silicon is 875 K. In one embodiment, the electrothermal voltage is less than or equal to 4 VDC. In another embodiment, the electrothermal voltage is less than or equal to 8 or 8.5 VDC. Those skilled in the art will understand that these voltages depend on the material of the electrode and its dimensions.

[0037] The resonant pressure sensor includes a frequency monitoring device 112 to monitor changes in the first symmetric resonant frequency and the second symmetric resonant frequency caused by the ambient pressure surrounding the

curved microbeam while the curved microbeam is electrothermally tuned by the applied electrothermal voltage and electrostatically driven at the first symmetric resonant frequency and the second symmetric resonant frequency by the applied AC signal. In one embodiment, the frequency monitoring device is a detection electrode. Preferably, the frequency monitoring device is a laser Doppler vibrometer. Any other device that can determine the frequency of the microbeam can be used for the pressure sensor.

[0038] In one embodiment, the resonant pressure sensor includes control electronics 110. The control electronics are in communication with the DC power source, the AC power source and the frequency monitoring device 112. Suitable control electronics include logical processors, computer storage and executable software configured to provide the desired functioning and monitoring for the resonant pressure sensor. In one embodiment, the control electronics use the monitored changes in the first symmetric resonant frequency and the second symmetric resonant frequency to determine the ambient pressure.

[0039] Referring now to Fig. 3, exemplary embodiments are directed to a method for sensing pressure 300, for example, using resonant pressure sensors as described herein. A desired material for the curved microbeam is selected 302. In one embodiment, the curved microbeam is silicon. The dimensions and initial curved displacement of the curved microbeam are identified 304. In one embodiment, the curved microbeam has dimensions and an initial rise at a midpoint along a length of the curved microbeam that produce strong veering between a plot of changes in the first symmetric resonant frequency with ambient pressure and changes in the second

symmetric resonant frequency with ambient pressure. In one embodiment, the curved microbeam has a length of 800 μm, an initial rise at the midpoint along the length of 2.6 μm, a width perpendicular to the length of 25 μm and a thickness perpendicular to the length and parallel to the initial rise of 1.5 μm. The curved microbeam has a plurality of resonant frequencies.

[0040] A DC power source is attached to opposing ends of the curved microbeam 305. An actuating electrode is positioned adjacent the curved microbeam 306. The actuating electrode extends along a length of the curved microbeam and is spaced from the curved microbeam. In one embodiment, positioning the actuating electrode adjacent the curved microbeam includes spacing the actuating electrode from the curved microbeam by a distance of at least 12μm. An AC power source is attached to the actuating electrode and one end of the curved microbeam 308.

[0041] The curved microbeam is electrothermally heated 310. In one embodiment, electrothermal heating the curved microbeam includes passing an electrothermal voltage from the DC power source along a length of the curved microbeam. Suitable electrothermal voltages are less than or equal to 4 VDC or less than or equal to 8 or 8.5 VDC. In one embodiment, passing the electrothermal voltage includes selecting the electrothermal voltage to cause a maximum rise at a midpoint along the length of the curved microbeam of less than 12μm and a temperature within the curved microbeam below a curved microbeam melting point.

[0042] The curved microbeam is electrostatically driven 312 at a first symmetric resonant frequency and a second symmetric resonant frequency selected from the plurality of resonant frequencies using the attached AC power source. In

one embodiment, the first symmetric resonant frequency is associated with a first symmetric vibration mode, and the second symmetric resonant frequency is associated with a second symmetric vibration mode. In one embodiment, the first symmetric vibration mode is a fundamental vibration mode, and the second symmetric vibration mode is a third vibration mode.

[0043] Changes in the first symmetric resonant frequency and the second symmetric resonant frequency caused by an ambient pressure surrounding the curved microbeam are monitored 314. In one embodiment, changes in the second symmetric resonant frequency are monitored when increases in the ambient pressure cause decreases in the second symmetric resonant frequency, and changes in the first symmetric resonant frequency are monitored when increases in the ambient pressure cause increases in the second symmetric resonant frequency. The monitored changes in the first symmetric resonant frequency and the second symmetric resonant frequency are used to determine the ambient pressure 316, and the determined ambient pressure is outputted 318. For example, the ambient pressure can be displayed or communicated to a requesting program or process.

[0044] Referring now to Fig. 4, an experimental setup 400 used to test the resonant pressure sensor is illustrated. The resonant pressure sensor 402, e.g., an arch MEMS resonator was placed inside a controllable test chamber 404 equipped with a pressure gauge 406. A DC voltage power source 408 was connected to the curved microbeam, and an amplifier 410 was connected to an end of the curved microbeam and the actuating electrode. A laser Doppler vibrometer 412, e.g., a Polytec (MSA 500), commercially available from Polytec GbmH of Waldbronn,

Germany, was positioned to measure resonant frequencies within the curved microbeam. The pressure within the test chamber was varied from 38 mTorr to atmospheric pressure. Therefore, the detection limit of the ambient pressure sensor, as tested, was 38 mTorr. The resonant pressure sensor was electrothermally tuned and electrostatically driven using the DC voltage power source and the amplifier. The laser Doppler vibrometer measured the resonant frequencies of the curved microbeam while the curved microbeam was driven electrostatically. The DC power source applied a voltage, V_{Th}, to induce a current flowing through the curved microbeam. The current heated the curved microbeam Joule's heating effect, altering the stiffness and resonant frequencies of the curved microbeam.

[0045] Frequency tuning of the resonant pressure sensor utilizes the effect of the induced compressive axial load in the curved microbeam due to the heating of the curved microbeam by electrothermal actuation. Heating increases the curvature of the curved microbeam and the stiffness of the curved microbeam. By choosing the geometrical parameters and the initial shape of the arch, the veering phenomenon (avoided-crossing) between two vibration modes, i.e., the first two symmetric vibration modes is strongly activated. Variations of the resonance frequencies of the curved microbeam around the veering zone, e.g., before, on, and after veering of the first two symmetric vibration modes, while applying a constant DC electrothermal voltage V_{Th} is studied. Therefore, the curved microbeam is configured deliberately to exhibit the veering (near crossing) phenomenon among two of its vibration modes, e.g., the first two symmetric vibration modes.

[0046] Referring to Fig. 5, changing V_{Th} 502 while maintaining the ambient pressure at low vacuum (38 mTorr) increases the first symmetric resonant frequency 504 up to twice its fundamental value due to the continuous increase in the curvature and stiffness of the curved microbeam. In addition, the third resonance frequency (f_3) 506 decreases. This decrease in the third resonance frequencies continues until the third resonance frequency approaches very close to the first resonance frequency (f_1) 508. After the curves approach very close, the curves of both the first and third resonance frequencies veer away from each other with a high curvature. Referring to Fig. 6, the same behavior is shown when the curved microbeam is operated at atmospheric pressure but for higher V_{Th}. The higher V_{Th} is used due to the cooling effect on the curved microbeam caused by the high pressure of the surrounding air. In addition to the experimental data 510 illustrated, for example, in Fig. 5, simulation results 512, obtained using a FEM model using COMSOL Multiphysics, are also illustrated. The simulation results indicate similar behavior to the experimental data.

[0047] The temperature of the curved microbeam, e.g., a silicon (Si) beam, is maintained below its melting point, i.e., 875 K, while being actuated by V_{Th}. The inset schematic 514 (Fig. 5) illustrates the FEM results of the maximum temperature and mid-point rise at 38 mTorr of the tested curved micro-beam with varying V_{Th}. These results are used to select the suitable electrothermal voltage to operate the curved microbeam with a maximum displacement lower than 12μm, i.e., the gap between the actuated electrode and the clamped end of the micro-beam, and a temperature

lower than 875 K. For the illustrated example, V_{Th}= 4 VDC was selected. The illustrated simulation indicates a maximum displacement of 7.3 μm and a temperature of 438 K at 4 VDC. The corresponding measured resonant frequency values near the first resonant mode (at 1 atm) and the third resonant node (at 38 mTorr) mode are 79 kHz and 169 kHz, respectively.

[0048] Referring to Fig. 7, experimental data obtained for the relative frequency shift Δf with the pressure p for the applied electrothermal voltage, $V_{Th,}$ at 4 V is illustrated. The ambient pressure was swept from 38 mTorr to atmospheric pressure. The relative frequency shift Δf is defined as $(f_0-f)/f_0$, where f_0 and f are the frequency of the microbeam at 38 mTorr and during the measurement with a given pressure, respectively. The results show five linear trends ((38 mTorr to 0.7 Torr) 702, (0.7 to 3.3 Torr) 704, (3.3 to 49 Torr) 706, (49 to 125 Torr) 708 and (125 Torr to 1 atm) 710). For each trend, the sensitivity (S) of the curved microbeam is calculated using the formula $f/(P_{max}- P_{min})$, where P_{max} and P_{min} are the maximum and minimum pressures, respectively. As shown, the first linear regime 702 shows the highest sensitivity against pressure (S = 47,473 ppm/Torr). The sensitivity decreases with the pressure.

[0049] Referring to Table 1, the sensitivity of the resonant pressure sensor 100 (illustrated in the last line of the table) is significantly higher compared with other previously reported pressure sensors.

TABLE 1: Summary of Some of the Reported Pressure Sensors

Materials	Pressure Range (Torr)	Max Pressure Detected (Torr)	Sensitivity ($Torr^{-1}$)	Optimal Value ($Torr^{-1}$)
Si/ZnO Si	112-6375	6375	5.46ppm	0.19ppm
Add Si	1,2,3,4,5,6,7,8,9,10	30	10,482ppm	3296ppm
p-Si	0-0.75	75	4341ppm	1413ppm
SiN	0.02-10	10	6918ppm	478ppm
Graphene/SiO_2/Si	150-750	750	3.95ppm	0.0023ppm
LRGO/DVD disk	0.0075-2.35	2.35	12000ppm	383ppm
Si	$38x10^{-3}$-10	200	27674ppm	153,170ppm
Si	$38x10^{-3}$-200	200	2689ppm	1446ppm

[0050] The results show a high sensitivity of 2689 ppm/Torr in a wide pressure range up to 200 Torr (detection limit), which is much higher than previous pressure sensors that were limited to 30 Torr. In general, the performance of a pressure sensor is related to the sensitivity (S) and the maximum detection limit (P). Thus, the relative frequency shift Δf multiplied by the sensitivity S can represent the performance of a pressure sensor (optimal value= ($S x \Delta f$) = ($S^2 x P$)). The optimal value of the resonant pressure sensor 100 is 153,170 ppm/Torr, which is much higher than the values associated with other pressure sensors as provided Table 1.

[0051] In addition to having a wide pressure range, the resonant pressure sensor 100 has a low power consumption. Power consumption is estimated based on resistive heating of the curved microbeam $(V_{Th})^2/R$, where R is the resistance of the microbeam 102. The resistance of the microbeam is estimated to be 1.34 kΩ. Thus, increasing the resistance of the microbeam will reduce the power consumption. The resonant pressure sensor 100 has a power consumption of around 12 mW. This power consumption is much lower than the power consumption associated with previous electrothermal actuated beams. The sensitivity and power consumption of the resonant pressure sensor 100 can be improved with a microbeam having a higher aspect ratio and construction from a material with a lower thermal conductivity. In one embodiment, the thermal response time of the curved microbeam is 162.8 s. To have a faster response time, the resonant pressure sensor is further miniaturized to a smaller size, e.g., to the nano- and submicron-scale.

[0052] To improve the sensitivity, FEM simulation of the resonant pressure sensor was conducted to evaluate the performance of the resonant pressure sensor and optimize the parameters of the resonant pressure sensor. To simulate the heat transfer between the solid and fluid domains, the Joule Heating and Thermal expansion module was coupled with the Conjugate Heat Transfer module. The maximum temperature as shown in Fig. 5 at 514 is calculated from the Joule's heating equation. Device sensitivity is dependent on the applied electrothermal voltage. A higher V_{Th} heats the microbeam more. Therefore, increased air volume, i.e., more pressure, is needed to cool down the microbeam.

[0053] Performance of the resonant pressure sensor 100 containing the curved microbeam is simulated at two operating voltages, 4 V and 8.5 V. Referring to Fig. 8, the percentage of relative frequency shift as a function of pressure is illustrated. Good agreement exists with the experimental data (see Fig. 7). The mismatch between the experimental and simulation results can be attributed to geometry imperfections. As shown in Fig. 9, the sensitivity decreases with the applied electrothermal voltage, because the curved microbeam is cooled down before reaching the transition point. Thus, the sensitivity is calculated from the third vibration mode. Sensitivity of the resonant pressure sensor at 1.2 Torr and V_{Th}= 4 V, which is equal to 127,185 ppm/Torr, is three times higher than sensitivity at 8.5 V. Sensitivity is expected to improve with higher applied electrothermal voltage. However, based on the veering phenomenon between the two symmetric modes, a lower voltage actuation shows higher sensitivity while consuming lower power.

[0054] Referring to Fig. 10, to further understand the effect of geometry on the veering phenomenon, and thus sensitivity, the variation of sensitivity with varying pressure for the same curved microbeam but with different thicknesses 1002, h, is illustrated. The transition point decreases with increasing thickness, h. Below the transition point pressure value, sensitivity decreases with increasing h, and above the transition point, sensitivity becomes higher for a thinner micro-beam. This suggests an optimum thickness for better sensitivity for low or high pressure depending on the targeted application. In addition, for a specific thickness, the third resonant frequency decreases until getting very close to the first symmetric resonant

frequency. This presents a method to choose the geometric parameters of such curved micro-beams carefully to activate the veering phenomenon.

[0055] Referring to Fig. 11, an optimal package size for optimal sensitivity is determined. At low pressure, sensitivity is much higher in the smaller volume. Sensitivity of the micro-beam at 2.35 Torr and for small package size of 1.5x1.5x1 mm^3, which equals to 125,919 ppm/Torr, is 1.5 times higher compared to the large package size (3.5x1.5x1 mm^3).

[0056] Exemplary embodiments are directed to a wide pressure range and highly sensitive resonant pressure sensor using a curved microbeam. The initially curved microbeam is electrothermally heated and exhibits veering phenomenon between two of its vibration modes, e.g., the first two symmetric vibration modes. The resonant pressure sensor exhibits high sensitivity, 2689 ppm/Torr, in wide pressure range, 38 mTorr to 200 Torr with a pressure limit of 200 Torr and an optimal value of 1446 ppm/Torr. Simulation through FEM illustrates the significant effect of thickness of the micro-beam, vacuum chamber size and thermal actuation load on the sensitivity of the resonant pressure sensor. In one embodiment for pressure sensor applications requiring high sensitivity, these parameters are optimized.

[0057] The foregoing written description uses examples of the subject matter disclosed to enable any person skilled in the art to practice the same, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the subject matter is defined by the claims, and

may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims.

WHAT IS CLAIMED IS:

1. A method for sensing pressure, the method comprising:

electrothermally heating (310) a curved microbeam (102) comprising a plurality of resonant frequencies;

electrostatically driving (312) the curved microbeam (102) at a first symmetric resonant frequency and a second symmetric resonant frequency selected from the plurality of resonant frequencies;

monitoring (314) changes in the first symmetric resonant frequency and the second symmetric resonant frequency caused by an ambient pressure surrounding the curved microbeam; and

using (316) the monitored changes in the first symmetric resonant frequency and the second symmetric resonant frequency to determine the ambient pressure.

2. The method of claim 1, wherein electrothermally heating the curved microbeam comprises passing an electrothermal voltage along a length of the curved microbeam.

3. The method of claim 2, wherein the electrothermal voltage comprises 4 VDC.

4. The method of claim 2, wherein passing the electrothermal voltage comprises selecting the electrothermal voltage to cause a maximum displacement at a midpoint

along the length of the curved microbeam of less than 12μm and a temperature within the curved microbeam below a curved microbeam melting point.

5. The method of claim 1, wherein the first symmetric resonant frequency is associated with a first symmetric vibration mode and the second symmetric resonant frequency is associated with a second symmetric vibration mode.

6. The method of claim 5, wherein the first symmetric vibration mode comprises a fundamental vibration mode and the second symmetric vibration mode comprises a third vibration mode.

7. The method of claim 1, wherein electrostatically driving the curved microbeam comprises using an AC power source in communication with the curved microbeam and an actuating electrode to deliver an AC signal to the curved microbeam, the actuating electrode extending along a length of the curved microbeam and spaced from the curved microbeam.

8. The method of claim 7, wherein the method further comprises:

spacing the actuating electrode from the curved microbeam by a distance of at least 12μm.

9. The method of claim 1, wherein the step of monitoring changes in the first symmetric resonant frequency and the second symmetric resonant frequency comprises:

monitoring changes in the second symmetric resonant frequency when increases in the ambient pressure cause decreases in the second symmetric resonant frequency; and

monitoring changes in the first symmetric resonant frequency when increases in the ambient pressure cause increases in the second symmetric resonant frequency.

10. The method of claim 1, wherein the method further comprises:

selecting the curved microbeam to have dimensions and an initial rise at a midpoint along a length of the curved microbeam that produce strong veering between a plot of changes in the first symmetric resonant frequency with ambient pressure and changes in the second symmetric resonant frequency with ambient pressure.

11. The method of claim 10, wherein the step of selecting the curved microbeam comprises:

selecting a curved microbeam wherein the length is 800 μm, the initial rise at the midpoint along the length is 2.6 μm, a width perpendicular to the length is 25 μm and a thickness perpendicular to the length and parallel to the initial rise is 1.5 μm.

12. A resonant pressure sensor (100) comprising:

a curved microbeam (102) comprising a pair of opposing ends (104), a length extending between the pair of opposing ends, and a plurality of resonant frequencies;

an actuating electrode (115) extending along the length of the curved microbeam (102) and spaced from the curved microbeam;

an AC power source (119) in communication with one of the opposing ends and the actuating electrode (115) to deliver an AC signal at a first symmetric resonant frequency and a second symmetric resonant frequency selected from the plurality of resonant frequencies to the curved microbeam (102);

a DC power source (108) in communication with the opposing ends (104) to pass an electrothermal voltage along a length of the curved microbeam (102); and

a frequency monitoring device (112) to monitor changes in the first symmetric resonant frequency and the second symmetric resonant frequency caused by an ambient pressure surrounding the curved microbeam (102).

13. The resonant pressure sensor of claim 12, wherein the curved microbeam comprises dimensions and an initial rise from the opposing ends at a midpoint along the length of the curved microbeam that produce strong veering between a plot of changes in the first symmetric resonant frequency with ambient pressure and changes in the second symmetric resonant frequency with the ambient pressure.

14. The resonant pressure sensor of claim 13, wherein the length is 800 μm, the initial rise at the midpoint along the length is 2.6 μm, and the curved microbeam comprises a width perpendicular to the length of 25 μm and a thickness perpendicular to the length and parallel to the initial rise of 1.5 μm.

15. The resonant pressure sensor of claim 12, wherein the actuating electrode is spaced from the curved microbeam by a distance of at least 12μm at the opposing ends of the curved microbeam.

16. The resonant pressure sensor of claim 12, wherein the first symmetric resonant frequency is associated with a first symmetric vibration mode and the second symmetric resonant frequency is associated with a second symmetric vibration mode.

17. The resonant pressure sensor of claim 16, wherein the first symmetric vibration mode comprises a fundamental vibration mode and the second symmetric vibration mode comprises a third vibration mode.

18. The resonant pressure sensor of claim 12, the electrothermal voltage comprises 4 VDC.

19. The resonant pressure sensor of claim 12, wherein the electrothermal voltage causes a maximum displacement at a midpoint along the length of the curved

microbeam between the opposing ends of less than 12μm and a temperature within the curved microbeam below a curved microbeam melting point.

20. The resonant pressure sensor of claim 12, wherein the frequency monitoring device comprises a laser Doppler vibrometer.

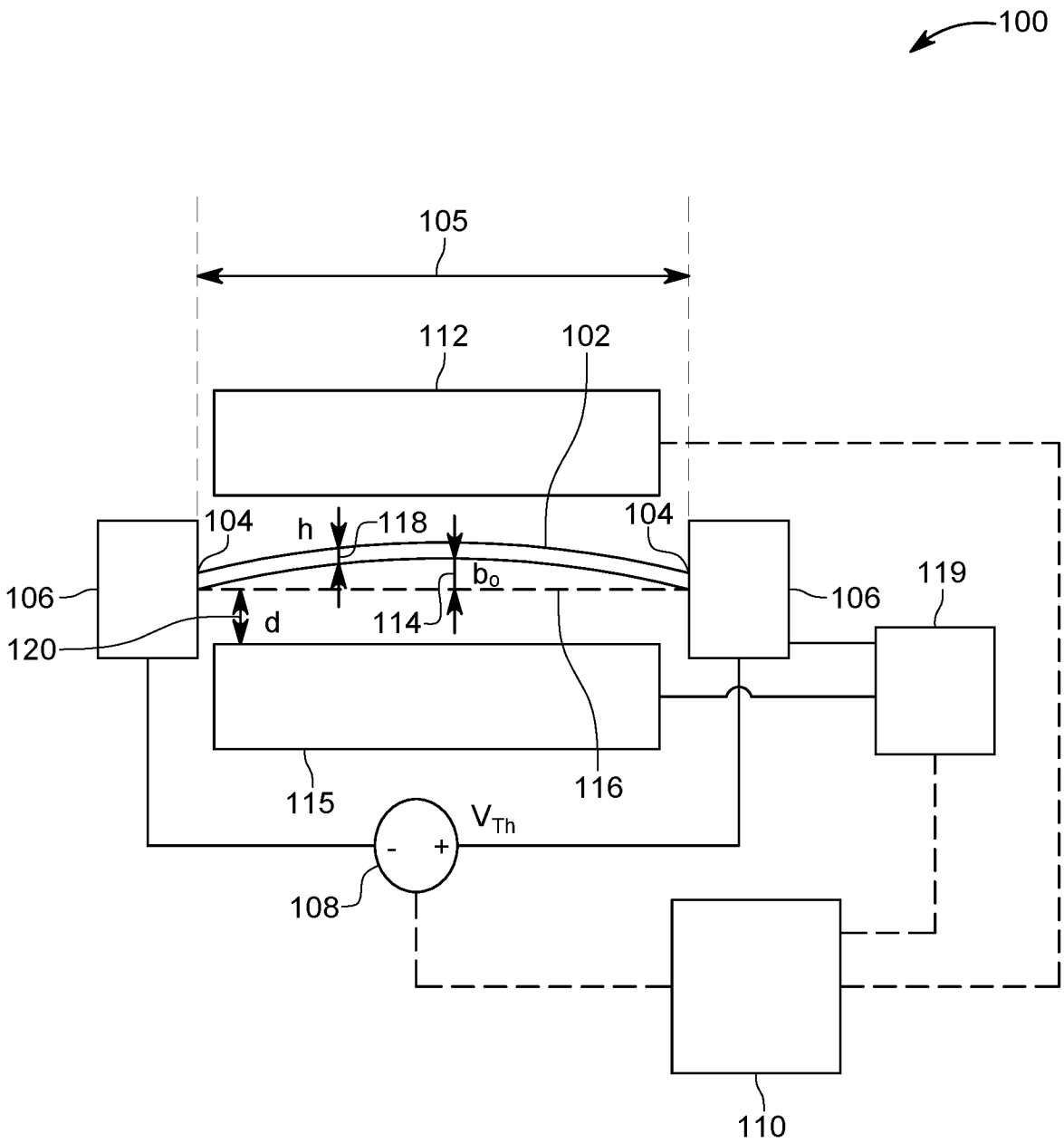

100
105
112
102
104
h
118
104
106
b_o
106
119
d
114
120
115
116
V_{Th}
-
+
108
110

FIG. 1

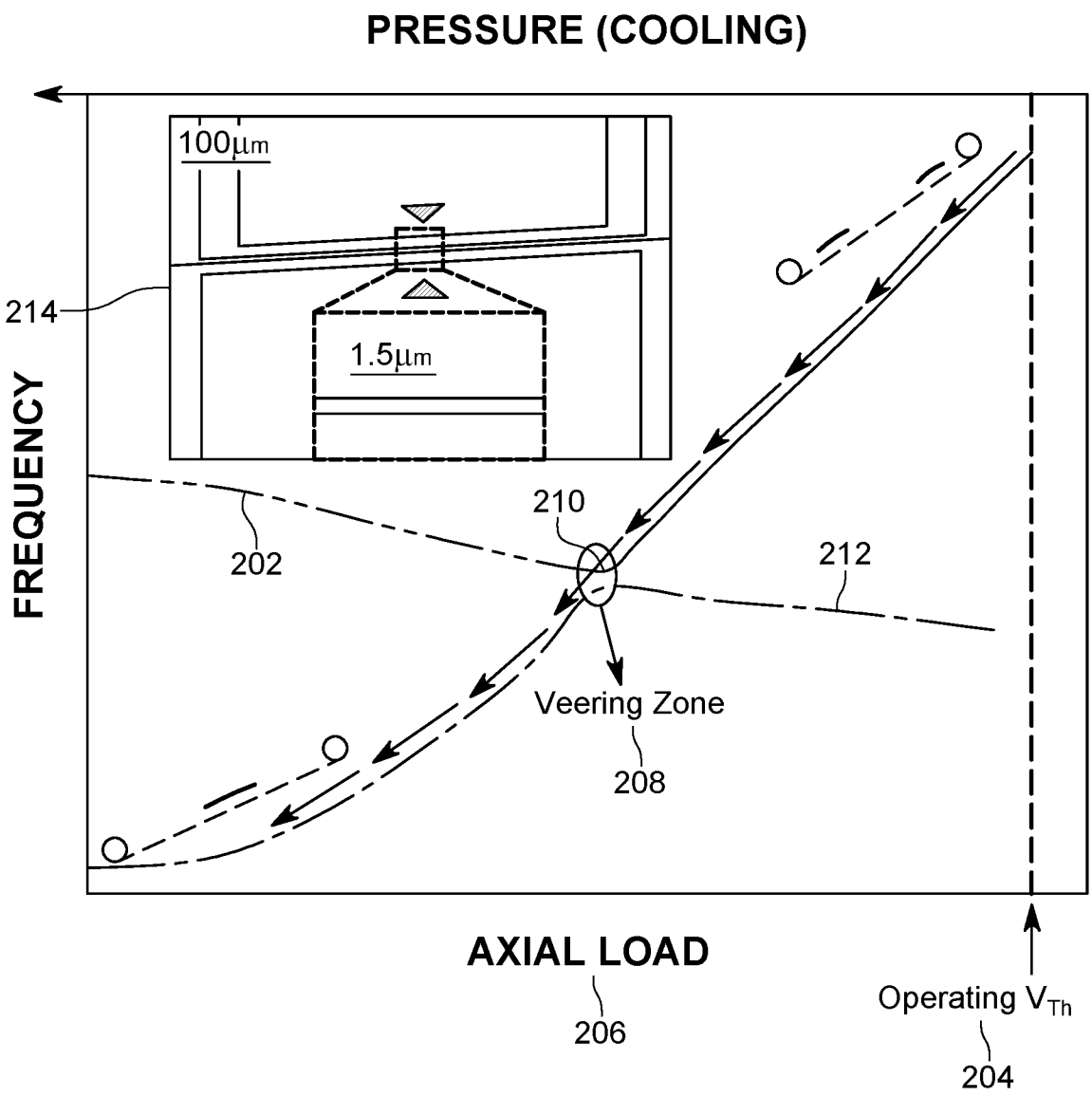

PRESSURE (COOLING)
100µm
214
1.5µm
FREQUENCY
202
210
212
Veering Zone
208
AXIAL LOAD
206
Operating V_{Th}
204

FIG. 2

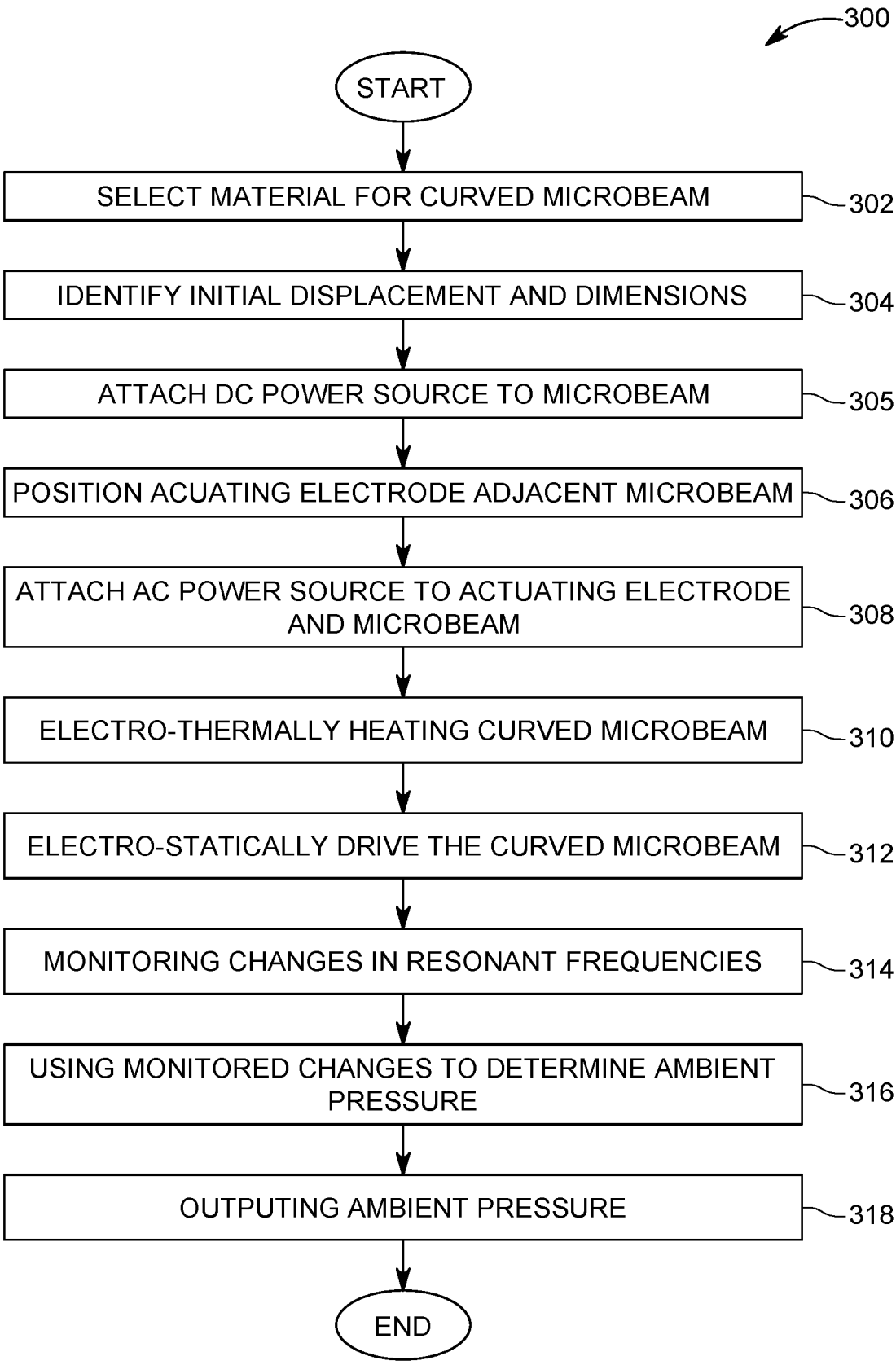

300
START
SELECT MATERIAL FOR CURVED MICROBEAM
302
IDENTIFY INITIAL DISPLACEMENT AND DIMENSIONS
304
ATTACH DC POWER SOURCE TO MICROBEAM
305
POSITION ACUATING ELECTRODE ADJACENT MICROBEAM
306
ATTACH AC POWER SOURCE TO ACTUATING ELECTRODE AND MICROBEAM
308
ELECTRO-THERMALLY HEATING CURVED MICROBEAM
310
ELECTRO-STATICALLY DRIVE THE CURVED MICROBEAM
312
MONITORING CHANGES IN RESONANT FREQUENCIES
314
USING MONITORED CHANGES TO DETERMINE AMBIENT PRESSURE
316
OUTPUTING AMBIENT PRESSURE
318
END

FIG. 3

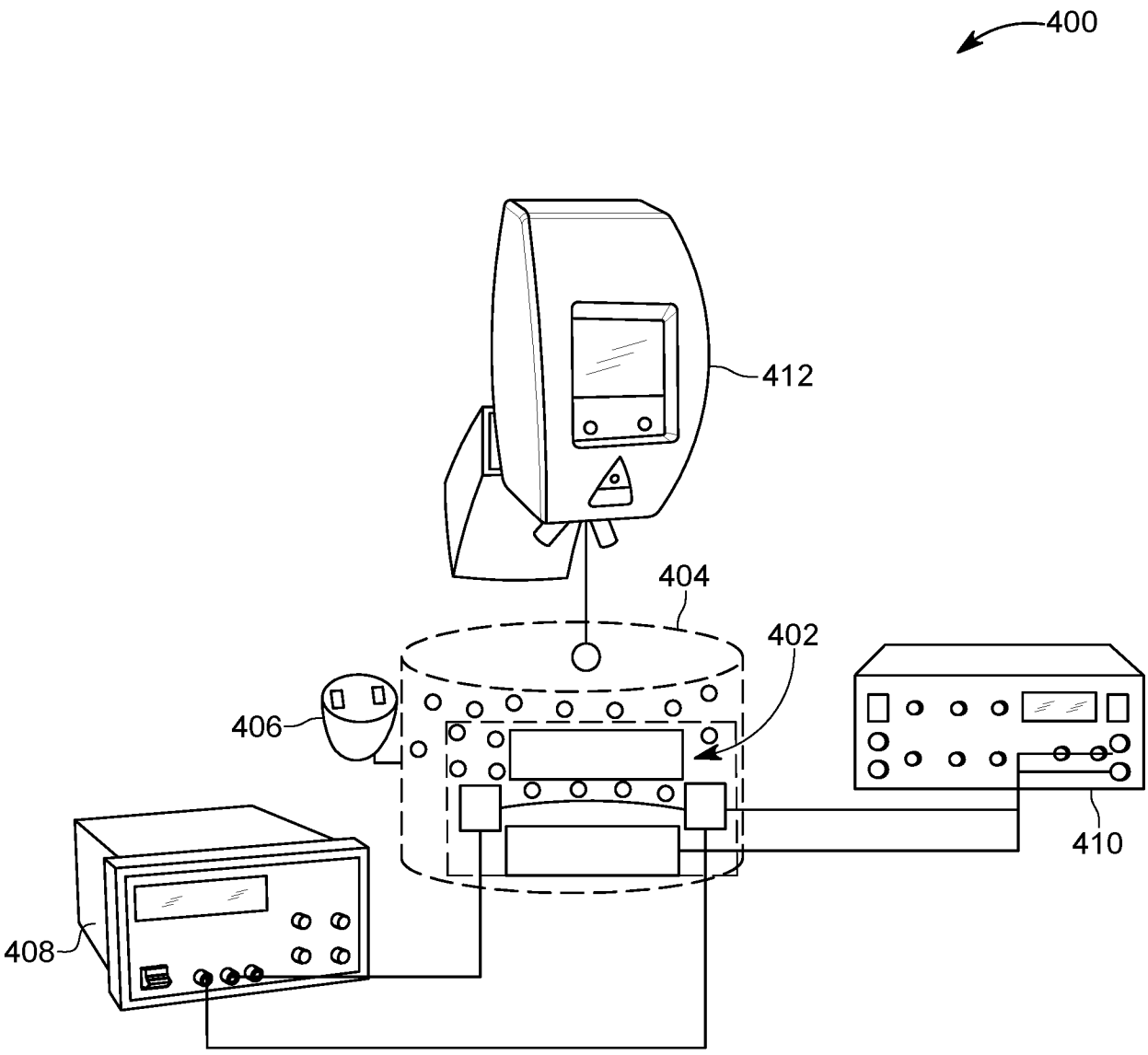


FIG. 4

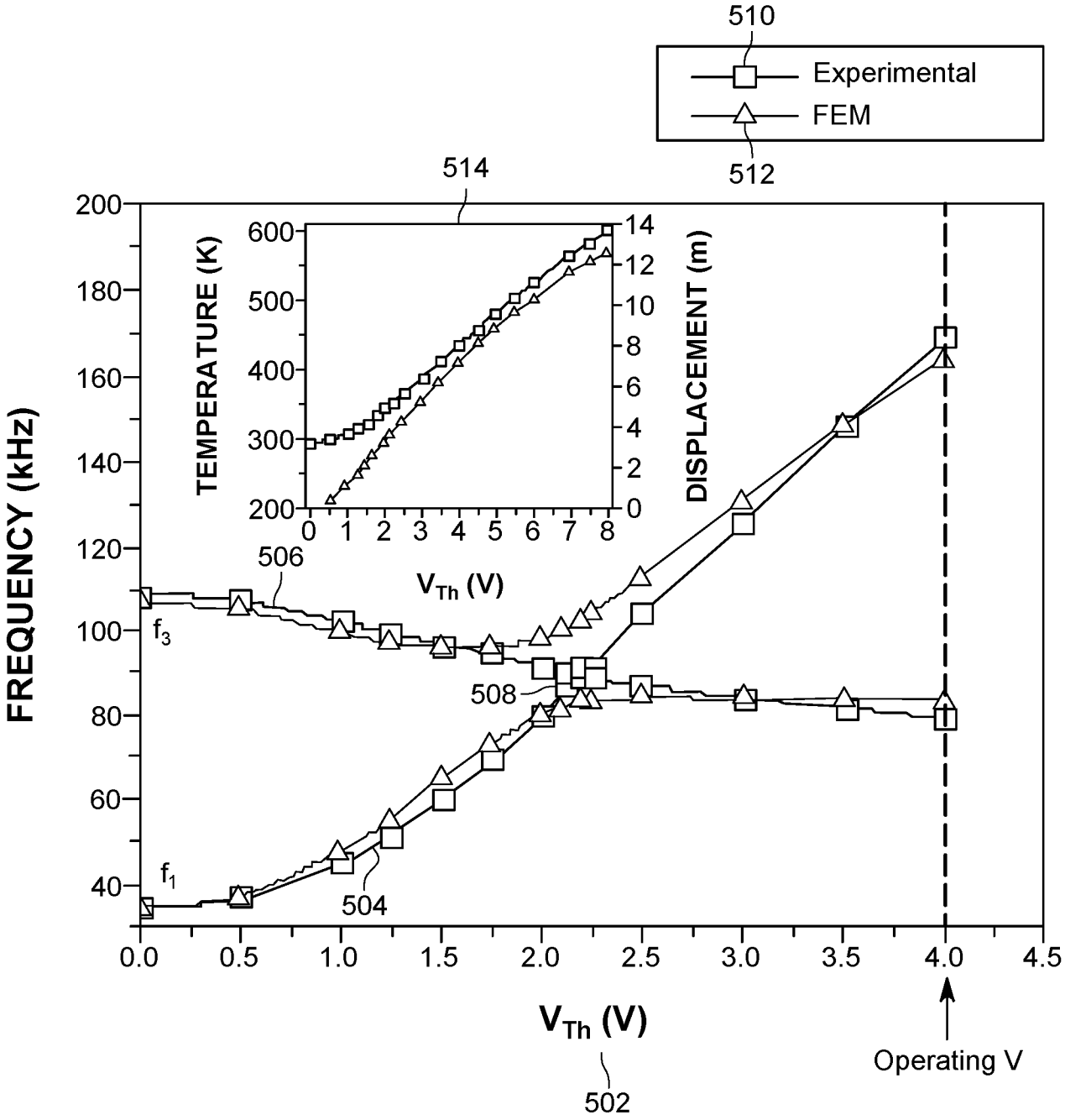

510
Experimental
FEM
512
514
FREQUENCY (kHz)
TEMPERATURE (K)
DISPLACEMENT (m)
V_{Th} (V)
506
f_3
508
f_1
504
V_{Th} (V)
502
Operating V

FIG. 5

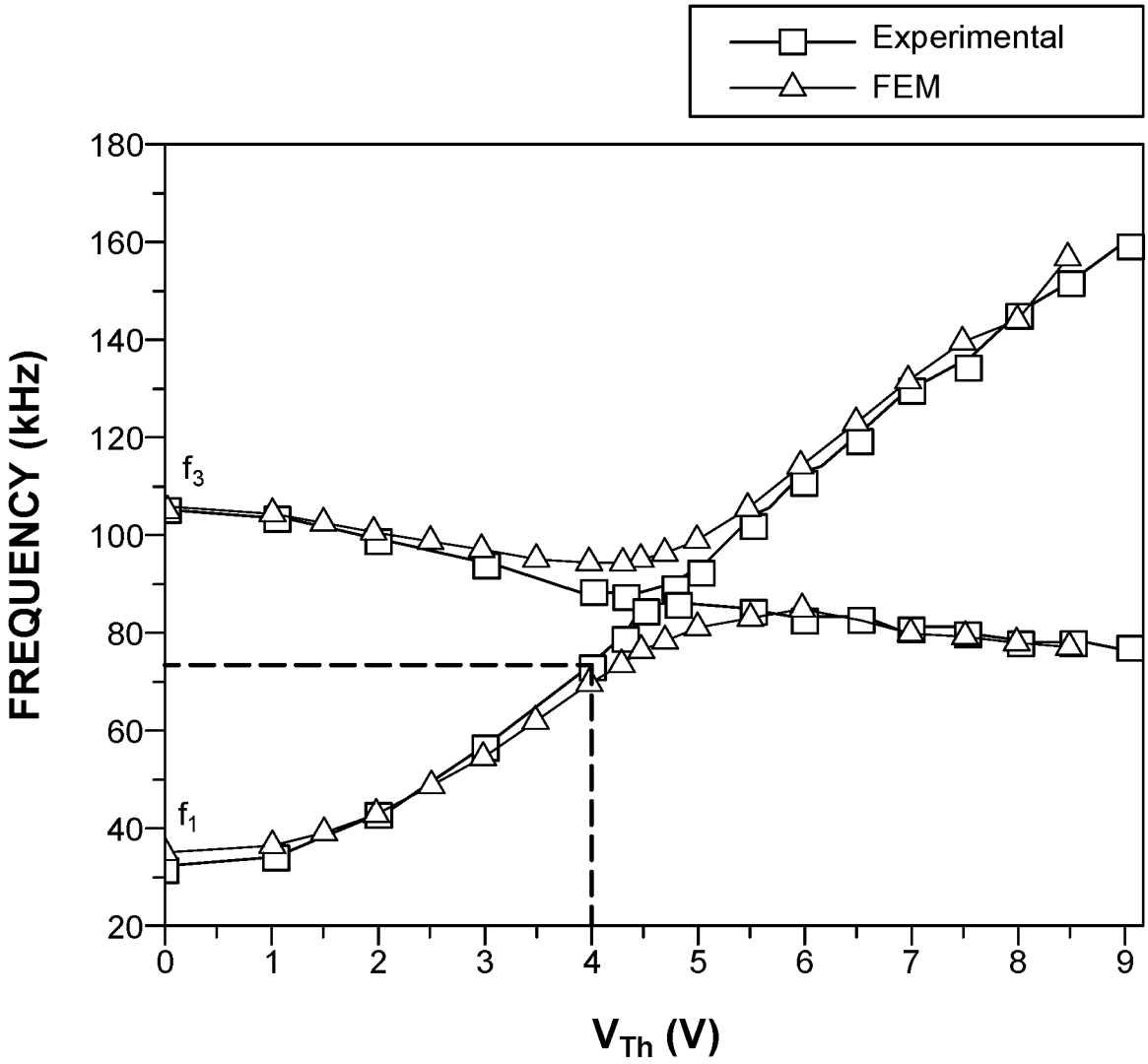

Experimental
FEM
FREQUENCY (kHz)
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
f_3
f_1
V_{Th} (V)

FIG. 6

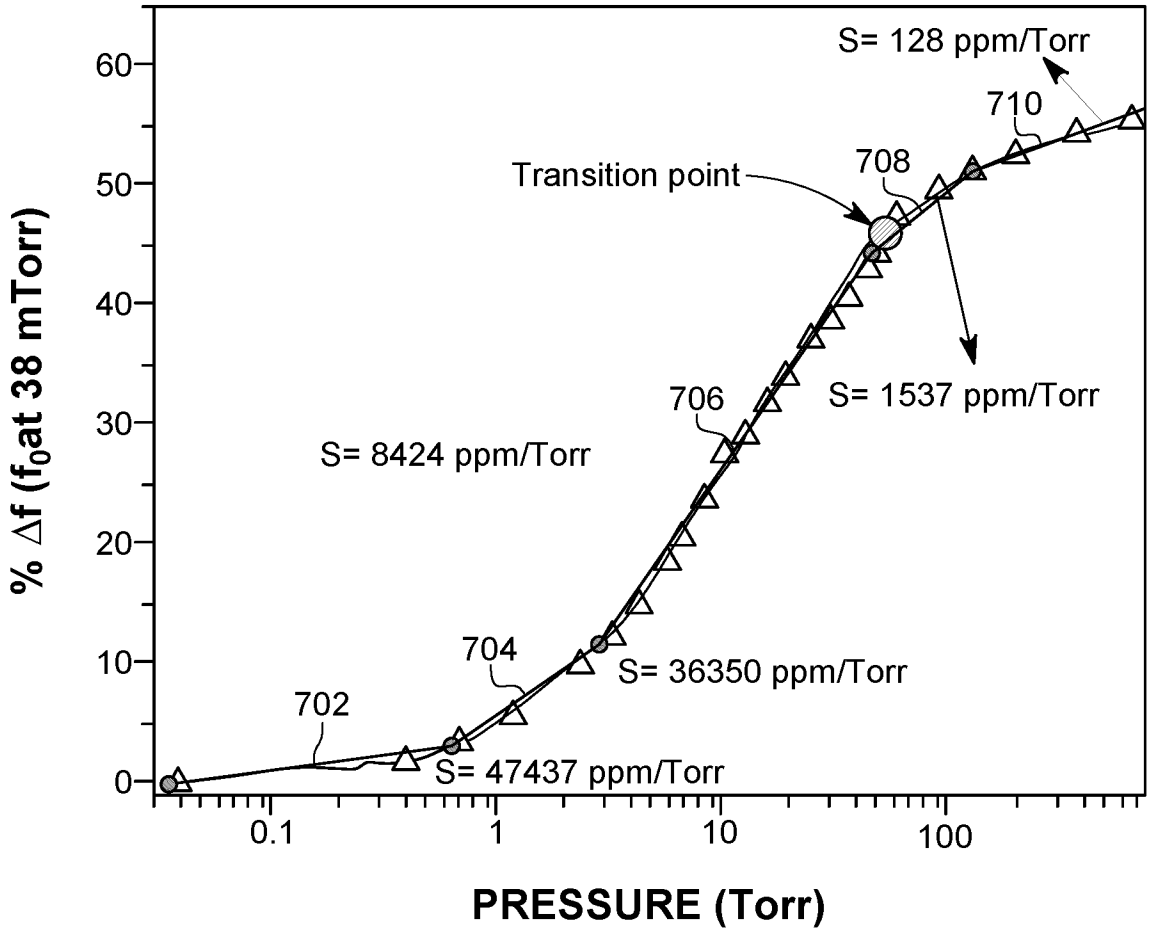

S= 128 ppm/Torr
710
708
Transition point
706
S= 1537 ppm/Torr
S= 8424 ppm/Torr
704
S= 36350 ppm/Torr
702
S= 47437 ppm/Torr
% Δf (f0at 38 mTorr)
PRESSURE (Torr)
0
10
20
30
40
50
60
0.1
1
10
100

FIG. 7

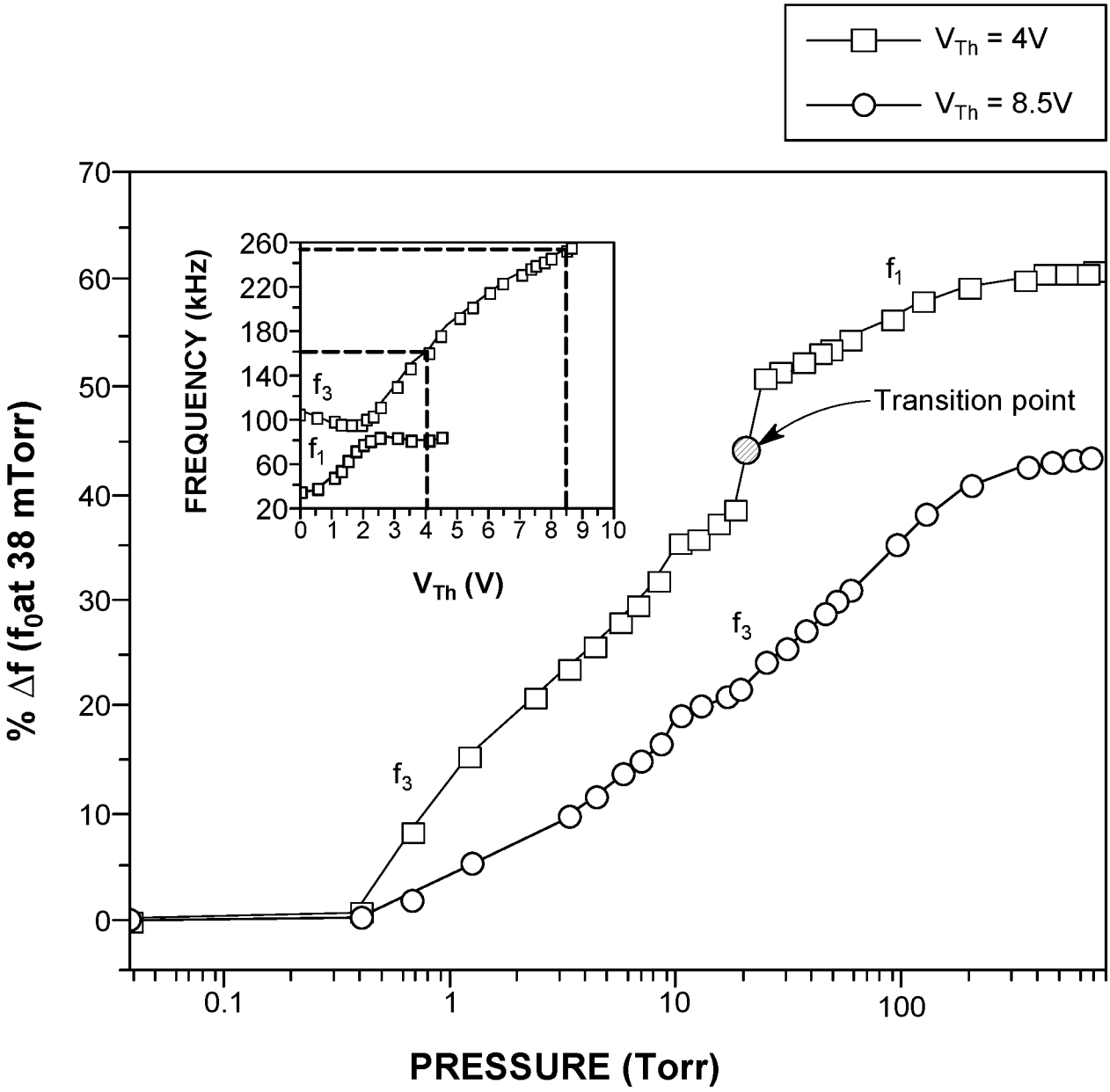

V_{Th} = 4V
V_{Th} = 8.5V
% Δf ($f_0$at 38 mTorr)
PRESSURE (Torr)
FREQUENCY (kHz)
V_{Th} (V)
f_1
f_3
Transition point

FIG. 8

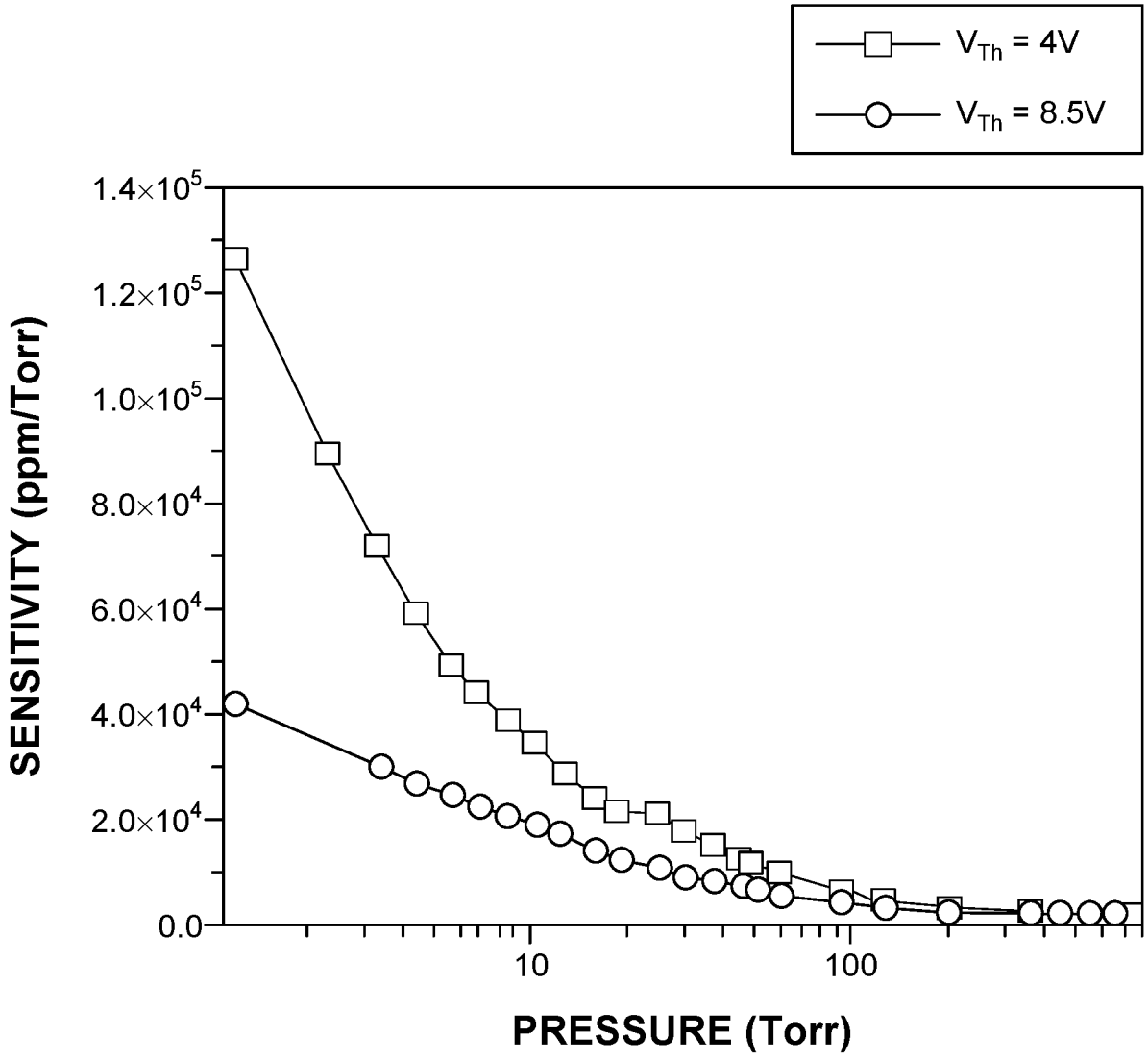

V_{Th} = 4V
V_{Th} = 8.5V
SENSITIVITY (ppm/Torr)
1.4×10^5
1.2×10^5
1.0×10^5
8.0×10^4
6.0×10^4
4.0×10^4
2.0×10^4
0.0
10
100
PRESSURE (Torr)

FIG. 9

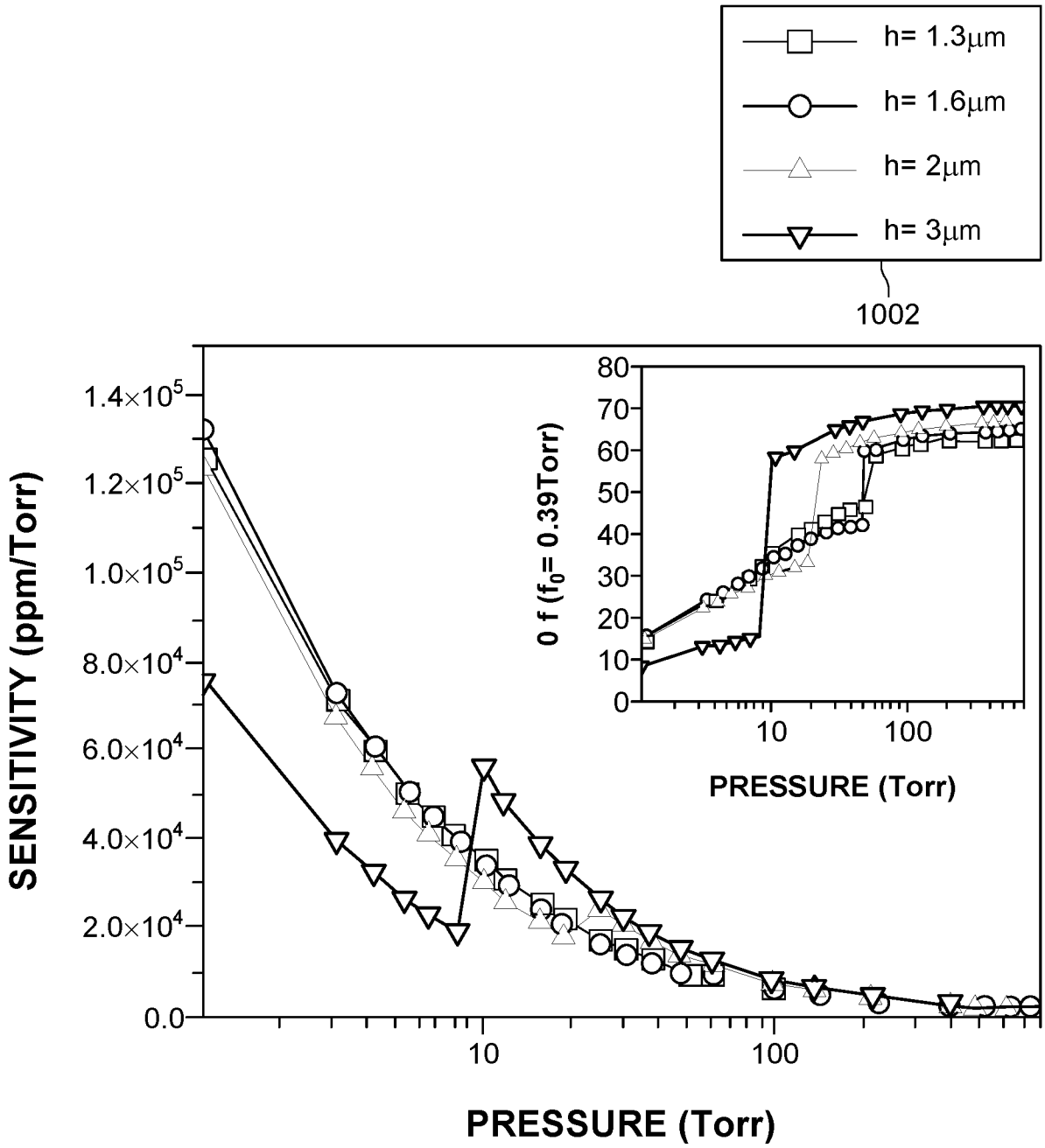

h= 1.3μm
h= 1.6μm
h= 2μm
h= 3μm
1002
SENSITIVITY (ppm/Torr)
1.4×10^5
1.2×10^5
1.0×10^5
8.0×10^4
6.0×10^4
4.0×10^4
2.0×10^4
0.0
10
100
PRESSURE (Torr)
0 f (f0= 0.39Torr)
80
70
60
50
40
30
20
10
0
10
100
PRESSURE (Torr)

FIG. 10

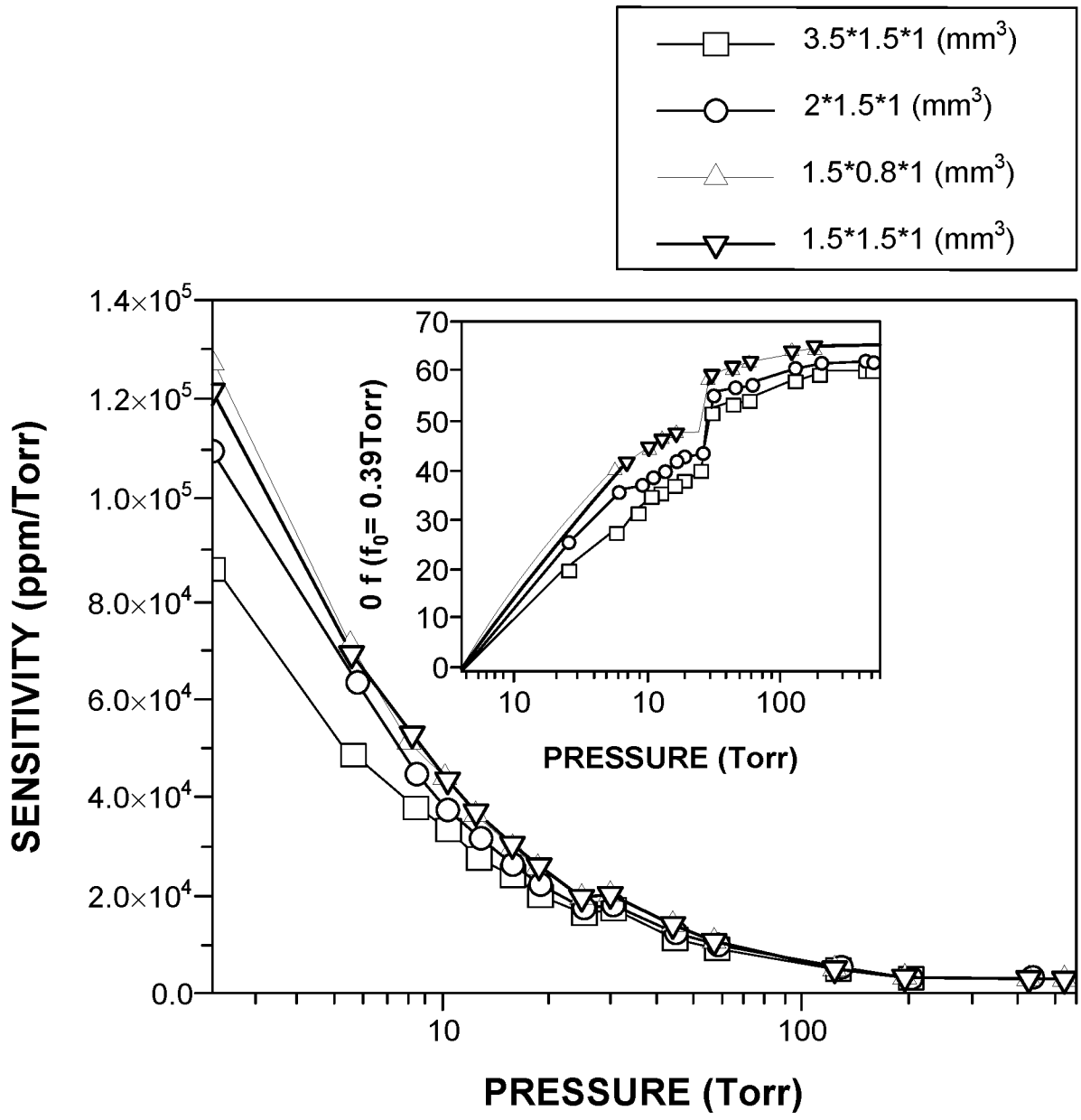

3.5*1.5*1 (mm3)
2*1.5*1 (mm3)
1.5*0.8*1 (mm3)
1.5*1.5*1 (mm3)
SENSITIVITY (ppm/Torr)
1.4×10^5
1.2×10^5
1.0×10^5
8.0×10^4
6.0×10^4
4.0×10^4
2.0×10^4
0.0
10
100
PRESSURE (Torr)
0 f (f0= 0.39Torr)
70
60
50
40
30
20
10
0
10
10
100
PRESSURE (Torr)

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2020/053571

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01L9/00 G01L21/22
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2019/021073 A1 (UNIV KING ABDULLAH SCI & TECH [SA]) 31 January 2019 (2019-01-31) abstract paragraphs [0002], [0005], [0020] - [0023] figures 1A,4A-4C,5 claims 11-15	1-20
Y	WO 2016/034940 A1 (UNIV KING ABDULLAH SCI & TECH [SA]) 10 March 2016 (2016-03-10) abstract paragraph [0134] claims 1-9 figures 1-34	1-20
A	US 2008/011091 A1 (WELDON JAMES P JR [US]) 17 January 2008 (2008-01-17) the whole document	1-20

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 June 2020	03/07/2020

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Daman, Marcel

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2020/053571

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KAZMI SYED N R ET AL: "Mechanical Computing Using Multifrequency Excited NEMS Resonator", 2018 IEEE 13TH ANNUAL INTERNATIONAL CONFERENCE ON NANO/MICRO ENGINEERED AND MOLECULAR SYSTEMS (NEMS), IEEE, 22 April 2018 (2018-04-22), pages 229-233, XP033466866, DOI: 10.1109/NEMS.2018.8556944 [retrieved on 2018-12-03] the whole document -----	1-20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2020/053571

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2019021073 A1	31-01-2019	NONE	
WO 2016034940 A1	10-03-2016	US 2017291811 A1	12-10-2017
		WO 2016034940 A1	10-03-2016
US 2008011091 A1	17-01-2008	NONE	