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An optically resonant position read-out system for MEMS gas sensors

Gino Putrino[a], Adrian Keating[b], Mariusz Martyniuk[a], Lorenzo Faraone[a], John M. Dell[a]

[a]School of Electrical, Electronic and Computer Engineering, The University of Western Australia, M018, 35 Stirling Hwy, Crawley, WA 6009, Australia;
[b]School of Electrical, Electronic and Computer Engineering, The University of Western Australia, M050, 35 Stirling Hwy, Crawley, WA 6009, Australia

ABSTRACT

We present an experimental demonstration of a novel, integrated readout approach for measuring the suspended height of micro-electro-mechanical systems (MEMS) structures. The approach is based on creating a resonant optical cavity between the suspended MEMS structure and the substrate that the MEMS structure is anchored to. The resulting interferometric effect causes modulation of an optical laser signal which is strongly dependent on the position of the MEMS device.

Keywords: MEMS; MOEMS; sensors; diffraction gratings; optical cavities

1. INTRODUCTION

One of the technologies that the emergence of the internet of things will require is a robust, widely deployable and accurate gas sensing technology. Gas sensors built from microelectromechanical systems (MEMS) have the potential to provide this technology.

MEMS gas sensors are extremely sensitive and can be functionalized using a number of techniques to create extremely specific sensing devices. Due to their small size, many hundreds, if not thousands, of sensors can be placed on a single chip, providing the opportunity for improving detection statistics, thermal compensation and also the potential for multi-analyte testing - where different structures next to each other could be functionalized for various substances. However, the wider commercial adoption and deployment of MEMS sensors has been prevented by the lack of a robust technology capable of measuring the nanomechanical movements of the MEMS sensors outside of laboratory environments.

In this work, we will present a novel read-out technique which integrates silicon photonics technology into MEMS sensors to provide picometer scale measurements of the movement of the MEMS sensors. The read-out technique is integrated into the silicon substrate of the MEMS device, and so rejects common mode noise. The technique has the ability to address large arrays of cantilevers, can operate in various environmental conditions, and is relatively easy to fabricate using silicon and CMOS compatible technologies.

2. MEMS GAS SENSORS

MEMS sensors are created by taking a MEMS structure - such as a cantilever or doubly clamped beam - coating it in an analyte which can preferentially bond to the substance that it is desirable to detect (this coating process is termed functionalization), and then watching the structure in order to observe a detection event. These sensors can be designed to operate in one of two main modes, designated in the literature as either static or dynamic mode.

Further author information:
G.P.: E-mail: gino.putrino@uwa.edu.au, Telephone: 61 8 6488 2559

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2.0.1 Static Mode

When the substance to be sensed bonds to a surface of a cantilever beam, surface stresses will be created, causing the cantilever beam to bend. Monitoring the movement of the cantilever tip will give an indication of whether a sensing event has occurred. Accurate measurement of the movement of the cantilever tip has led to the demonstrated ability to measure mass with zepto-gram (10^{-21}) sensitivity.[1] This technique is best used with long, thin and compliant MEMS cantilevers.

2.0.2 Dynamic Mode

Mechanical structures have a characteristic frequency that they prefer to vibrate at. This is known as their resonant frequency, and is proportional to the mass, physical dimensions, and other properties of the mechanical structure. For sensors based on MEMS resonators, when the substance being sensed bonds to the mechanical structure, the mass of the structure, and therefore the resonant frequency of the structure will change. This technique is best used with thick, rigid MEMS beams with high resonant frequencies.

2.1 Sensing Applications

MEMS sensors provide such an attractive opportunity to create low-cost, highly accurate, miniature sensers that a substantial amount of work has been performed in this field. As early as 1939, Norton described the use of a cantilever based chemical sensor in his US patent named "Gas Analyzer".[2] However, it was not until 1969, that Shaver[3] used this technique to demonstrate the detection of hydrogen at a sensitivity of 50 ppm using large 100 mm long, 125 μm thick cantilevers. This early device was rather large, and could only barely considered MEMS in that only one dimension (the thickness of the cantilever) was micro-scaled.

What was arguably the first true MEMS gas sensor was not demonstrated until 1986, when Howe and Muller fabricated a resonant microbridge xylene vapor sensor by depoiting a polymer film on a poly-silicon microbridge.[4,5] This MEMS sensor prototype displayed a responsivity of around 0.3 Hz/ppm, which compared favorably to alternative sensing techniques at the time.

The potential of these devices triggered a large research effort into sensing applications, and before long, several research groups had demonstrated the sensing of simple chemicals and then moved towards applying this technique to more complex biological samples.

Thundat *et al.* performed work demonstrating the detection of relative humidity,[6] mercury vapour,[7] toulene and mercaptans.[8] Once again, these approaches showed incredibly sensitive results. The frequency response of the mercury vapour cantilever sensor was shown to be 11 pg/Hz, and even in an unoptimized experimental setup, the minimum detection level of the mercaptans was 50 parts per billion (ppb).

Due to the ease of mass fabrication of MEMS devices, arrays of cantilever beams on chips were soon implemented. Many cantilevers were desired in order to give better detection statistics, the ability for simultaneous multianalyte sensing, and the provision of reference cantilevers which were not functionalized to provide a measure of thermal drift. At the turn of the millenium, several research groups demonstrated such arrays with up to eight cantilever sensors on a single device.[9–11]

The range of chemicals these devices could sense is only limited by the ability of chemists to find specific functionalization layers.[12,13] Therefore, soon MEMS sensors were demonstrated to be able to detect many different types of chemicals, ranging from explosives such as TNT and RDX,[14] or pesticides such as DDT.[15] MEMS sensors were also shown to be able to perform medical tasks such as the rapid detection of bacterial resistance to antibiotics,[16] diagnosing head and neck cancer through the analysis of breath[17] or detecting skin cancer melanomas.[18] It is predicted that this last technique can be applied to other cancers such as gastrointestinal stromal tumours and lung cancer.[19]

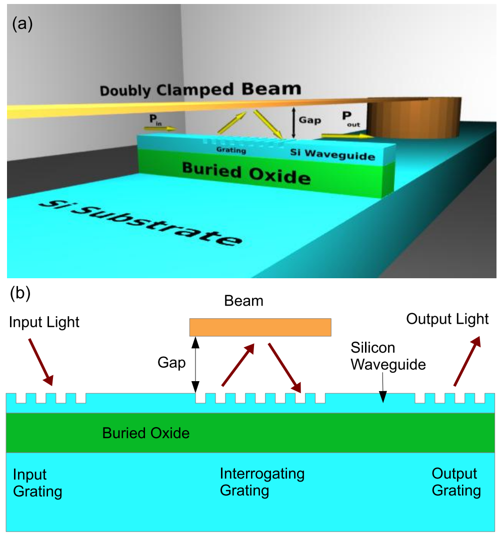

Figure 1. (a) Isometric view of the proposed interrogating grating structure. (b) Cross section of the full device.

2.2 Readout Techniques

Critical to the operation of this type of sensor is the method of detecting the height change (for static mode) or motion (for dynamic mode) of the MEMS beam to determine whether a detection event has occurred. Less critical, but still eminently desirable is the ability to address large numbers of MEMS beams, as large arrays of beams provide improved detection statistics, the ability to perform multianalyte sensing, and the opportunity to allow non-functionalized beams available to provide a thermal compensation measurement.

A large number of MEMS sensor readout techniques have been demonstrated over the past twenty years. These readout techniques can generally be grouped into either optical or electronic techniques. The optical techniques the use of light reflected from the cantilever tip to a distant quadrant detector (optical beam deflection)[20] or sensing based on optical interferometry.[21] Electrical sensing techniques investigated have included piezoresistive, piezoelectric, capacitive, Lorentz force/emf sensing and tunneling current techniques.

Generally speaking, optical techniques have far higher resolution than electronic techniques, yet electronic techniques are capable of addressing far larger numbers of cantilevers than optical techniques. Optical techniques have the additional benefit of being able to operate in fluidic environments.

Recent work investigating MEMS beam readout has focused on approaches that have the ability to read compact very large arrays. Zinoviev *et al.* proposed a technique which uses the sensing cantilever as an optical waveguide and reported a theoretical shot noise limited deflection noise density (DND) of 1880 $\mathrm{fm}/\sqrt{\mathrm{Hz}}$.[22] Pham *et al.* used the dielectric properties of a cantilever to peturb the evanescent field of a diffraction grating approximately 400 nm below the cantilever tip,[23] and reported a minimum detectable deflection (MDD) as low as 54 pm. Stievater *et al.* proposed photonic microharp sensors which have the potential for very large arrays,[24] although the problem of coupling light to each sensing microharp is non-trivial. This technique has a DND quoted as being in the tens of $\mathrm{fm}/\sqrt{\mathrm{Hz}}$.

3. NOVEL READOUT CONCEPT

A next generation technology for the position readout of MEMS gas sensors will require the high resolution of optical techniques, combined with the ability to address large arrays that integrated electronics can provide. The novel readout concept described in this work provides this, and is schematically shown in Figure 1. For gas sensing applications, the doubly clamped beam shown will move, changing it's height or mechanical resonance frequency in response to an adsorbed analyte. To sense such movements, an optically resonant cavity is created when a micromachined beam with a reflective undersurface is suspended above a diffraction grating etched into a waveguide.

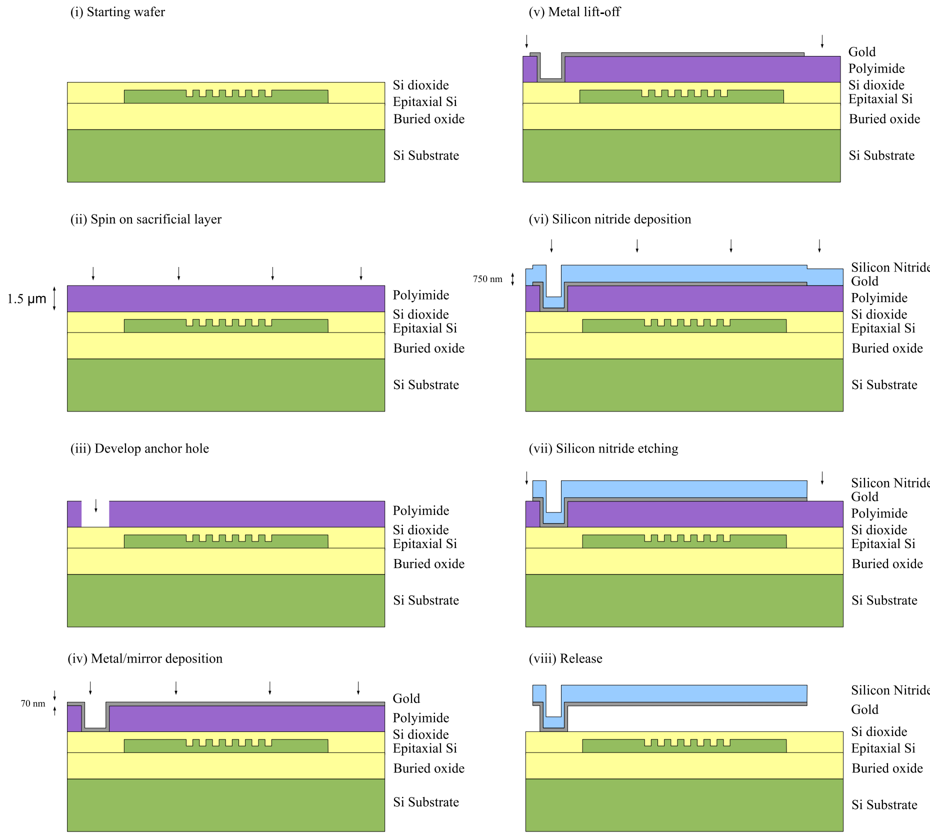

Figure 2. (a) Isometric view of the proposed interrogating grating structure. (b) Cross section of the full device.

The diffraction grating is designed to be efficient for light in the mid-infrared. When infra-red light travels through the silicon waveguide, the grating will diffract some of the light out of the waveguide towards the micromachined beam. The mirror on the micromachined beam will reflect the light back towards the grating. The recombination of the remaining light in the waveguide with the reflected light leads to constructive and destructive interference in the light out of the waveguide, creating an interferometer. As a result, the intensity of the light travelling through the waveguide is amplitude modulated by movement of the micromachined beam (due to interferometer path length change).

4. FABRICATION

The waveguides and diffraction gratings were fabricated using a silicon on insulator (SOI) wafer by the LETI standard passive process using the ePIXfab silicon photonics platform. The buried oxide (BOX) layer was 2 μm thick, and the epitaxial silicon was 220 nm thick. The waveguides and gratings (pitch 630 nm, depth 70 nm) were etched into the silicon using a deep ultra-violet (DUV) lithography process. Silicon dioxide was then deposited to cover the structures and chemo-mechanically polished (CMP) down to a thickness of 100 nm above the waveguides in order to supply a flat surface for further fabrication steps.

Plasma enhanced chemical vapour deposition (PECVD) silicon nitride was used as the structural material to fabricate MEMS microbridges with a gold undercoat using surface micro-machining.[25] The gold was 50 nm thick in order to provide good reflection for the infra-red light that was used in the experiment (at wavelengths of 1550, 1585, and 1610 nm). The beams were 220 μm long and 20 μm wide, with top hat style anchors. The sacrificial layer used was the low stress polyimide PI-2610 of thickness of 1.6 μm. This process flow is shown in Figure 2.

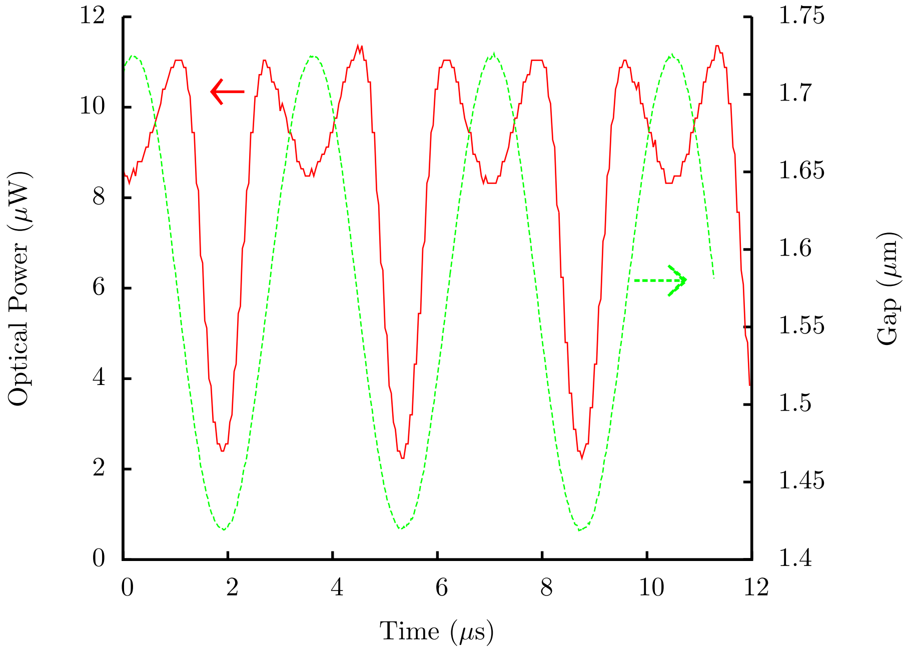

Figure 3. Measured 1585 nm laser optical power and displacement for the actuated microbridge with respect to time.

5. RESULTS

The chip was bonded to a piezo-electric device which was used to drive the microbridge at its resonant frequency of 291 kHz. A Polytec OFV-5000 vibrometer controller with a DD-500 displacement decoder was used to monitor the displacement of the microbridges to determine the gap between the suspended beam and the waveguide and to measure the mechanical resonance frequency. 1585 nm laser light was coupled into the integrated silicon photonics waveguide on the chip, and the output from the photodiode measured with an InGaAs photodiode. Figure 3 presents the optical power output as well as the separation between the microbridge and the interrogating grating as a function of time. As can be seen from this figure, the optical power is very strongly modulated over the 250 nm distance between the underside that the center of the microbridge travels, giving a very high resolution measurement of the postion of the microbridge beam. The power output is not completely monotonic of the range that the microbridge is actuated. This is due to the inteferometric nature of the technique, and is expected.

6. CONCLUSION

This work has presented an experimental demonstration of an integrated system for measuring the height position movement of a suspended doubly-clamped beam. The readout technique is scalable, and with the use of integrated germanium photodiodes integrated on chip, the technique could by used to address massive arrays of beams on a chip. Although this experiment was performed using microbridges, we believe that the technique is easily extended to microcantilevers and other MEMS structures.

ACKNOWLEDGMENTS

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