MEMS Nanomechanical Membrane-Flexure Sensors with Integrated Electromechanical Transduction : Design, Fabrication and Application Development

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by

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Abstract

Nanomechanical cantilever sensors (NMC) have emerged as a suitable candidate for bio/-chemical sensing applications which works by translating molecular interaction caused by various analytes on cantilever surface into nanomechanical motion that can be detected by suitable transduction schemes. The device structure modification and integration of highly sensitive transduction materials to NMC sensors can bring considerable improvement in sensor performance leading to ultra-sensitive nanomechanical sensor platforms. This research work focuses on developing an optimized membrane-based sensor platform , which meets the demand for highly sensitive, miniaturized real-time sensors. The electromechanical transduction of the sensor is performed by integrating a high gauge factor low-temperature sputter-deposited Indium Tin Oxide (ITO) thin film as piezoresistor.

The first part of the research work aimed at developing an optimized polymer-based NMC sensor with embedded ITO thin film piezoresistor. Microcantilever being the simplest and well-studied MEMS sensor platform, it is appropriate to incorporate the ITO thin film on the NMC sensor platform to study its candidature as strain sensing material. Polymers such as SU-8 has been chosen as the structural material for the development of the NMC sensor as they have reduced Young's modulus compared to silicon and hence can be exploited for improved sensitivity. With simple and cost-effective polymer MEMS process integration, low temperature deposited ITO has been incorporated for efficient electromechanical transduction of SU-8 microcantilever devices. The fabricated SU-8/ITO microcantilevers were experimentally characterized for extracting the mechanical, electrical and electromechanical properties. The fabricated microcantilever devices exhibited deflection sensitivity of 37 ppm/nm and very high force sensitivity (1% change in resistance per μN load). These SU-8/ ITO devices exhibited the highest sensitivity among piezoresistive microcantilevers reported in literature. A room temperature hydrogen leak detector with sub-ppm sensing capability was developed using these devices. Hydrogen gas of 1000 ppm concentration was successfully detected by the palladium coated SU-8/ITO cantilever.

Despite the promising performances, piezoresistive microcantilevers suffer from reduced sensitivity compared to optical transduction, which limits their use in bio/chemical applications demanding ultra sensitivity. The shortcomings of piezoresistive microcantilever sensors in terms of sensitivity for surface stress sensing applications could be resolved by a membrane-based sensor architecture. The main part of the research work thus introduces a Nanomechanical Membrane-Flexure (NMF) sensor with integrated electromechanical transduction using ITO thin film piezoresistor. The NMF structure consists of a circular adsorbate membrane suspended by four inverse trapezoidal flexures. The silicon and polymers such as SU-8 have been chosen as the structural material for the sensor considering the superior structural property and suitability for adopting conventional silicon MEMS microfabrication methods of the former and cost-effectiveness and ease of fabrication of the latter.

ITO thin film was experimentally characterized to extract its electrical, mechanical, and electromechanical properties to assess its candidature in integrating as strain sensing element with nanomechanical sensors. The gauge factor of ITO thin film was measured using a high precision four-point bending fixture experimental setup. An ultra-thin ITO film deposited at room temperature with no oxygen flow and post-annealing treatments exhibited a high negative gauge factor of -430, making it an excellent candidate in the nanomechanical sensor platform. The fabrication of silicon and polymer NMF sensors along with device characterization for evaluating their performance has been carried out as part of this work. The optimized design of the piezoresistive silicon NMF sensor exhibited a deflection sensitivity which is almost 16 times higher than conventional cantilever sensors. The surface stress sensitivity of the proposed device is nearly 15 times higher than cantilever sensors, making it an excellent candidate as an ultra-sensitive bio/chemical sensor. Finally, the application of this silicon NMF sensor for the detection of 100-1000 ppm concentration of H_2 gas with good sensitivity and fast recovery has also been demonstrated with a suitable laboratory prototype as part of the research work.

The final part of the research work investigated TMDC based two-dimensional materials with scope for strain-sensitive field-effect transistor (FET) integration to MEMS. For this, wafer-scale synthesis methods were developed for MoS_2 FETs to integrate on NMF sensors for ultra-sensitive active transduction.

Key words: Nanomechanical cantilever, electromechanial transduction, Indium Tin Oxide, polymer microcantilever, SU-8, hydrogen detection, nanomechanical membrane-flexure sensor, four-point bending fixture, MoS_2