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A low-cost rate-grade nickel microgyroscope

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Abstract

This paper presents a low-cost microgyroscope with a resolution in the rate-grade at atmospheric pressure, which is fabricated using a CMOS-compatible nickel electroforming process. Angular rate resolution of the gyroscope is increased by matching the resonance frequencies of the drive and sense modes close to each other using symmetric suspensions and electrostatic frequency tuning; whereas, undesired mechanical coupling between the two modes during matched mode operation is reduced by the fully decoupled gyro flexures. Reduced mechanical coupling results in a stable zero-rate output bias, i.e., providing excellent bias stability. The fabricated gyroscope has 18 μm-thick nickel structural layer with 2.5 μm capacitive gaps providing an aspect ratio above 7, which results in sensor capacitances about 0.5 pF. The resonance frequencies of the fabricated gyroscope are measured to be 4.09 kHz for the drive-mode and 4.33 kHz for the sense-mode, which are then matched by a tuning voltage less than 12 V dc. The gyroscope is hybrid connected to a CMOS capacitive interface circuit, and the hybrid system operation is controlled by external electronics, constructing an angular rate sensor. The gyroscope is oscillated along the drive-mode to vibration amplitude above 10 μm. The rate sensor demonstrates a noise-equivalent rate of 0.095 (°/s)/Hz$^{1/2}$ and short-term bias stability better than 0.1 °/s. The nominal scale factor of the sensor is 17.7 mV/(°/s) in a measurement range of ±100 °/s, with a full-scale nonlinearity of only 0.12%. The measurement bandwidth of the gyroscope is currently set to 30 Hz, while it can be extended beyond 100 Hz depending on the application requirements. The quality factor of the sense-mode improves by an order of magnitude at vacuum, which yields an estimated noise-equivalent rate better than 0.05 (°/s)/Hz$^{1/2}$ in a narrowed response bandwidth of 10 Hz.

Keywords: Gyroscope; Angular rate sensor; Decoupled oscillation modes; Nickel electroforming

1. Introduction

There are several applications that require reliable, low-cost, and small-size angular rate sensors, including automotive roll-over detection and industrial platform stabilization. Major performance requirements of these applications are rate-grade resolution and bias stability, both being less than 0.5 °/s [1]. These specifications are not difficult to achieve by using advanced silicon micromachining technologies such as polysilicon trench-refill [1], dissolved wafer process [2], SOI micromachining [3], silicon-on-glass micromachining [4], polysilicon surface micromachining [5], silicon bulk micromachining [6], and SOI wafer bonding to glass substrates [7]. The common features of these technologies are the high-performance at the expense of increased fabrication complexity and limited yield. In addition, monolithic integration of these fabrication processes with CMOS processes are difficult, requiring hybrid integration of the gyroscopes and CMOS electronics that increases the packaging cost. On the other hand, Analog Devices has developed CMOS-integrated inertial gyroscopes for the low-cost market [8]. These gyroscopes are fabricated with a dedicated BiCMOS manufacturing process, but the thickness of the structural polysilicon is limited to few microns. The performance of these gyroscopes is highly-improved by successful monolithic integration of the gyroscope with the high-quality readout electronics. However, the process is a dedicated process requiring high start-up and development costs. Approaches based on post-CMOS MEMS fabrication such as post-CMOS metal electroforming are attractive, since they allow to use low-cost standard CMOS foundry processes. Therefore, there are approaches in the literature to develop electroformed gyroscopes that are compatible with standard CMOS processes [9]. However, the gyroscopes developed based on electroforming have limited performances due to their low aspect ratio processes and structural limitations, resulting

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in small sensor capacitances and drive-mode vibration amplitudes. Therefore, for low-cost rate-grade applications, it would be attractive to develop a dedicated microgyroscope structure that can be fabricated with a simple, low-cost, high-aspect-ratio, and CMOS-compatible electroforming technology.

This paper reports a new low-cost rate-grade microgyroscope fabricated with a simple and CMOS-compatible nickel electroforming process [10]. The new structure allows electrostatic tuning of resonance frequencies and large drive-mode oscillation amplitudes for enhanced sensitivity, as well as having a dedicated flexure design that minimizes mechanical cross-talk between drive and sense modes of the gyroscope due to process variations. The overall sensitivity and bias stability of the fabricated gyroscope satisfies the rate-grade performance with excellent nonlinearity in a large full-scale range and with a bandwidth sufficiently high for many applications.

2. Gyroscope structure

Fig. 1 shows the simplified three-dimensional model of the gyroscope. The proof mass is electrostatically driven into resonance along *y*-axis using linear comb drive electrodes. When the gyro frame is rotated about *z*-axis, part of the energy stored in the oscillating proof mass couples to the *x*-axis, causing the sense electrodes move along the *x*-axis. This coupled motion creates a capacitance change, which is detected using a CMOS capacitive interface circuit. The output signal from the interface circuit is then processed by external electronics providing an electrical output proportional to the applied angular rate input. Suspension flexures and anchorage of the structure is designed to restrict the motion of the movable drive and sense electrodes to 1 degree-of-freedom (DOF), whereas only the proof mass is allowed to 2 DOF motion. This configuration minimizes undesired mechanical cross-talk between the drive and sense modes. The drive-mode of the gyroscope is optimized for large amplitude and linear driving oscillations using linear comb fingers, whereas the sense-mode is optimized for increased rate sensitivity and electrostatic tuning using varying-gap type comb fingers. Finally, flexures are designed symmetric along the drive and sense modes for minimizing possible temperature-dependent drift [11].

3. Fabrication process

Fig. 2 shows the fabrication process flow that requires only three masks. The process starts with deposition and patterning of 300/3000 Å-thick evaporated Cr/Au metallization layer over a 500 μm-thick, 4-inch, Corning 7740 Pyrex glass substrate. Next, a 300/3000 Å-thick Ti/Cu seed layer is sputter-coated on the whole substrate surface. The Ti/Cu seed layer is then etched away inside the anchor and pad metallization regions, for ensuring that the nickel is electroformed on Cr/Au stack rather than on Ti/Cu stack at the structural layer formation step towards the end of the process (Fig. 2h). Otherwise, nickel structures detach from the substrate surface during long sacrificial layer etch at the final step of the process. Following the patterning of a 5.5 μm-thick negative-tone photoresist (Microposit ma-N 440) with controllable-sidewall profile, the copper sacrificial layer is electroformed from copper sulfate chemistry on the whole substrate surface except inside the anchor regions. Next, the negative-tone photoresist is stripped from the substrate surface and Shipley's SJR5740 photoresist is coated to a thickness of about 20 μm and patterned using the structural layer mask. After cleaning the surface of the underlying conductive Ti/Cu and Cr/Au seed layer regions with oxygen plasma and hardbaking the structural photoresist mold, nickel is electroformed inside the thick photoresist mold from a low-stress nickel sulphamate chemistry. Finally, the thick photoresist mold is stripped in the SVC175 photoresist stripper, and the copper sacrificial layer and the Ti/Cu seed layer are selectively etched in a mixture of 1:1:18 acetic acid (CH_3COOH), H_2O_2, and deionized water. Fabricated nickel gyroscopes are then cleaned in deionized water, rinsed in a standard acetone–isopropyl alcohol (IPA)–methanol bath, and released by drying on hotplate.

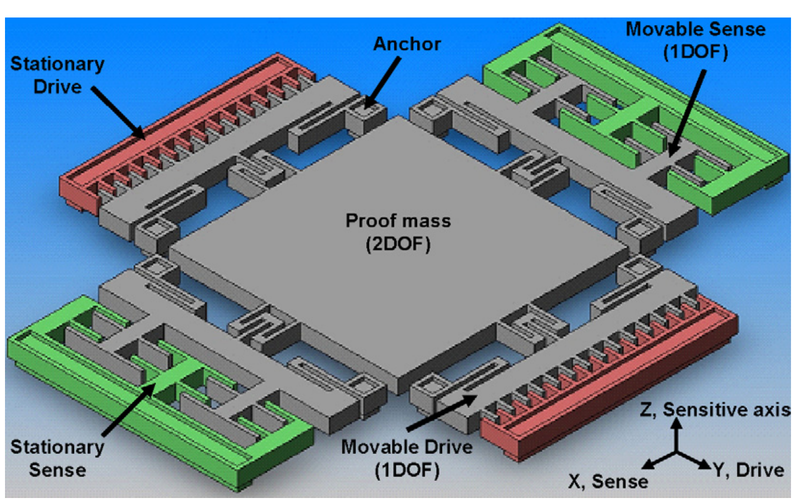

Fig. 1. Simplified three-dimensional model of the gyroscope with symmetrically-located and decoupled suspension flexures and anchorage restricting the motion of the movable drive and sense electrodes to 1 degree-of-freedom (DOF), whereas only the proof mass is allowed to 2 DOF motion. The structure has linear drive combs allowing large drive-mode vibration amplitudes, large sense capacitances with electrostatic tuning capability, and folded flexures for linear drive-mode vibrations.