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Formation of thick SU-8 mold for the fabrication of UV-LIGA based nickel micro-gyroscope structures

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Abstract: SU-8 is a high contrast, epoxy based negative tone photoresist designed for MEMS and other microelectronic applications, where a thick, chemically and thermally stable image is desired. However, in practice, SU-8 is found to be very sensitive to process parameters variation. This paper reports an optimized process for creating thick SU-8 mold and its application in the fabrication of UV-LIGA based nickel micro-gyroscope structures. Initial experiments are carried out on 4 inch silicon wafers with two different micro-gyroscope structures, a 2-DOF linear micro-gyroscope having minimum feature size of 5 µm and a 4-DOF linear micro-gyroscope having minimum feature size of 3 µm. The patterned SU-8 is examined using scanning electron microscopy (SEM) and is found to be completely resolved having near vertical side walls. Finally, the micro-gyroscope structures are successfully fabricated using SU-8 based UV-LIGA process having 10 µm thick nickel as the key structural layer.

Keywords: SU-8, UV-LIGA, Nickel micro-gyroscope, Electroforming.

Tvorba debelega SU-8 ulitka za proizvodnjo strukture nikljevega mikro žiroskopa na osnovi UV-LIGA

Izvleček: SU-8 je visoko kontrasten negativni fotorezist na osnov epoksija za MEMS in ostale mikroelektronske aplikacije, kjer je potrebna debela in kemijsko in termično stabilna slika. Kakorkoli, SU-8 se je v praksi izkazal zelo občutljiv na spremembo procesnih parametrov. Članek predstavlja optimalen proces za izdelavo debele ulitka in njegovo uporabo pri izdelavi nikljevega mikro žiroskopa. Prvi poskusi so bili izvedeni na 4 inčni silicijevi rezini z dvema različnima strukturama mikro žiroskopa: 2-DOF linearen žiroskop z minimalno velikostjo 5 µm in 4-DOF linearen žiroskop z minimalno velikostjo 3 µm. SU-8 vzorec je bil pregledan s pomočjo elektronske mikroskopije (SEM), ki je pokazala popolnoma vertikalne stranske stene. Končno so bili žiroskopi uspešno izdelan na osnovi UV-LIGA z 10 µm ključno plastjo niklja.

Ključne besede: SU-8, UV-LIGA, nikljev mikro žiroskop, elektroformacija

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1 Introduction

UV-LIGA is an important technology that empowers economic mass production of micro-structures with high aspect ratios for MEMS applications /1/. The core difficulty with this technology is the use of UV or near-UV lithography to form thick micro-molds for electroforming /2/. One of the most employed photoresist for this purpose is SU-8 with properties of high viscosity and low optical absorptions in the near-UV range, which make it an ideal material for generating thick structures for electroforming /3/. However, as feature sizes get smaller and pattern complexity increases, particular difficulties; like planarization defects, film stress and solvent gradients, resist UV absorption, long development times, collapse of structures during rinsing; and a number of material related issues arise and need to be carefully considered /4/.

The micro-gyroscope structure has a perforated proof-mass, suspension system consisting of thin flexible beams which suspend the proof-mass above the substrate and comb-drives with narrow gap between the fingers for electrostatic actuation and capacitive sensing. Hence, the problems mentioned earlier are prominent in creating thick SU-8 mold for micro-gyroscope. Also, there is no published work on SU-8 processing specially for micro-gyroscope structures. In this paper, an optimized process for creating thick SU-8 mold for the fabrication of UV-LIGA based nickel micro-gyroscopes is reported. Two different micro-gyroscope structures are successfully fabricated using the given process.

The rest of the paper is organized as follows. Section 2 describes briefly the structures of proposed micro-gyroscopes. In section 3, lithographic processing of SU-8 and challenges faced are discussed. Section 4 illustrates the complete fabrication process of UV-LIGA based nickel micro-gyroscope and SEM images of fabricated structures.

2 Proposed micro-gyroscope structures

The fundamental operation principle of micro-gyroscope relies on the sinusoidal coriolis force induced due to the combination of vibration of a proof-mass and an orthogonal angular-rate input. The proof-mass is generally suspended above the substrate by a suspension system consisting of thin flexible beams. For exciting the micro-gyroscope, the most common actuation methods are electrostatic, piezoelectric, magnetic and thermal actuation. Most common coriolis response detection techniques include capacitive, piezoelectric, piezoresistive, optical, and magnetic detection. However, electrostatic actuation and capacitive detection are known to offer several benefits compared to other sensing and actuation means /5/. Comb-drives with narrow gap between the fingers are vastly used for electrostatic actuation and capacitive sensing in micro-gyroscope. For our study, we have taken two different micro-gyroscope structures, a 2-DOF linear micro-gyroscope and a 4-DOF linear micro-gyroscope.

Fig. 1 shows the conceptual schematic of proposed structure of 2-DOF linear micro-gyroscope /6/. The design is optimized to be compatible with UV-LIGA process having 10 µm thick nickel as the key structural layer. The device has a perforated proof-mass of 2.56 mm × 2.56 mm. The size of the perforation is 10 µm square with spacing of 10 µm. The width of each of the suspension beam is 6 µm. The gap between comb fingers is kept as 5 µm.

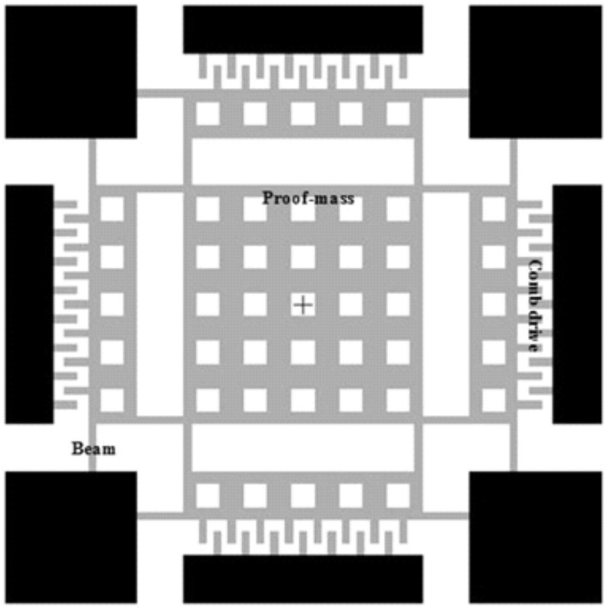

Figure 1: Conceptual schematic of proposed structure of 2-DOF linear micro-gyroscope

Fig. 2 shows the conceptual schematic of proposed 4-DOF linear micro-gyroscope /7/. The first mass m_1 and the combination of the second and third masses (m_2+m_3) form a 2-DOF drive mode oscillator. Whereas, m_2 and m_3 are free to oscillate independently in the sense direction, forming a 2-DOF sense mode oscillator. Mass m_f acts as the decoupling frame. The design is optimized to be compatible with UV-LIGA process having 10 µm thick nickel as the key structural layer. The device has a perforated proof-mass of 4.17 mm × 4.17 mm. The size of the perforation is 8 µm square with spacing of 10 µm. The width of each of the suspension beam is 5 µm. The gap between comb fingers is kept as 3 µm. It is evident from the schematic of Fig. 2 that the pattern complexity is increased in 4-DOF linear micro-gyroscope compared to 2-DOF linear micro-gyroscope.

3. Lithographic processing of SU-8

SU-8 is an acid-catalyzed negative tone photoresist. It is made by dissolving EPON®-SU-8 resin in an organic solvent such as cyclopentanone solvent or GBL (γ-butyrolactone) and adding a photoinitiator. The viscosity, and hence the range of thickness accessible, depends on the ratio of solvent to resin. The EPON resist is a multifunctional, highly branched epoxy derivative that contains bisphenol-A novolak glycidyl ether. On average, a single molecule consists of eight epoxy groups, which explains the "8" in the name SU-8 /8/. In a chemically amplified photoresist like SU-8, one photon produces a photoproduct that in turn causes hundreds of reactions to change the solubility of the film /9/.

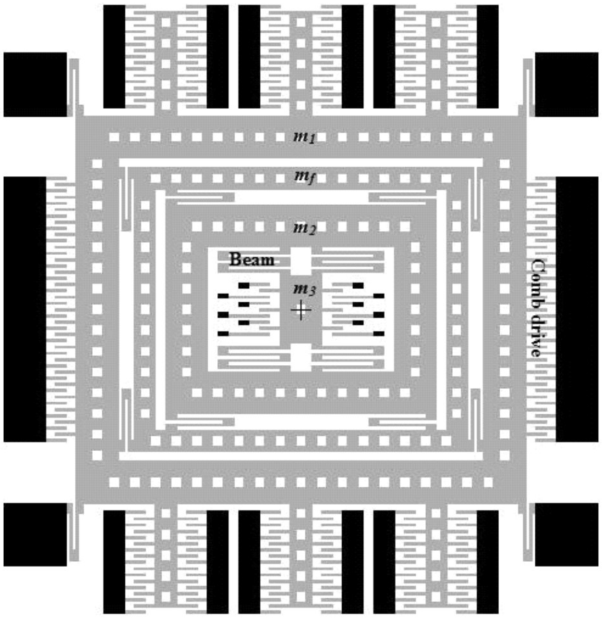

Figure 2: Conceptual schematic of proposed structure of 4-DOF linear micro-gyroscope

Initial experiments for SU-8 processing are carried out on 4 inch silicon wafers with a native oxide layer. Silicon wafers are cleaned by standard degreasing and piranha cleaning. After every cleaning the wafers are rinsed thoroughly in de-ionized water and are then blown dried with filtered compressed nitrogen gas. After that, the wafers are kept in a convection oven at 140 °C for 30 min to remove any moisture on wafer surface. MCC's Omnicoat is then spin-coated onto the cleaned wafer at 3000 rpm for 30 s. It is recommended by MCC to apply Omnicoat for applications that require electroplating and subsequent removal of SU-8. It also acts as an adhesion promoter /10/. The coated wafers are baked in a convection oven at 140 °C for 1 hour. After that, MCC's SU-8 2010 is spin-coated onto the wafer at 1500 rpm for 30 s. The wafers are then soft-baked at 65 °C for 7 min and 95 °C for 14 min in a convection oven. This step is required to remove the solvent and improve resist-substrate adhesion. However, baking temperature and time has to be selected properly. Higher soft-bake temperatures may initiate thermal cross-linking even if photoactivation has not taken place. On the other hand, lower soft-bake temperatures or shorter soft-bake time leave resist films with a high solvent content which will evaporate and therefore generate high film stress during post-exposure baking. The wafers are cooled down to room temperature after soft-baking. After that, the SU-8 is exposed to 365 nm UV light having an intensity of 30 mW/cm^2 with masks of 2-DOF linear micro-gyroscope and 4-DOF linear micro-gyroscope. We have used multiple exposure technique to achieve near vertical side walls. The exposure time is optimized as two exposures of 1.4 s each with wait time of 10 s between the exposures. Again, exposure time is one of the crucial parameter as overexposure will result in unresolved features and underexposure will result in peeling off of resist during the development step. The wafers are then kept in a convection oven at 65 °C for 7 min and 95 °C for 14 min for post-exposure baking. A post-exposure bake increases the cross linking degree in the exposed areas of SU-8 and stabilizes them against the action of solvents during the development step. At the end of the post-exposure bake, the wafers are cooled down to room temperature to release the residual stress. Development is performed by immersing the wafers in MCC's SU-8 developer at room temperature followed by rinsing in isopropanol. The development time is optimized as 50 s. Finally, the wafers are hard-baked at 140 °C for 1 hour in a convection oven. The hard-baking of photoresist is essential to prevent seepage of plated material under the photoresist during electroforming.

The patterned SU-8 is examined using scanning electron microscopy (SEM). The SU-8 is coated with gold prior to SEM examination. The SEM images of SU-8 molds made for final micro-gyroscope structures are shown in Fig. 3 for 2-DOF linear micro-gyroscope and in Fig. 4 for 4-DOF linear micro-gyroscope. It is evident that pattern is completely resolved having near vertical side walls. The thickness of the mold is measured using surface profiler and it is found to be 11 µm.

4 Micro-gyroscope structure fabrication

The micro-gyroscope structures are fabricated using three mask UV-LIGA process described in Fig. 5. The process starts by growing 1 **µm** thick thermal oxide on 4 inch silicon wafer. Next, a 300/2000 Å thick Ti/Au metallization layer is sputtered and patterned to make contact pads. Again, a 300/2000 Å thick Ti/Au metallization layer is sputtered on the whole wafer surface to act as seed layer. After that, 11 **µm** thick resist MCC's SU8 2010 is patterned and 8 **µm** thick copper sacrificial layer is electroformed on the whole substrate surface except on the anchor regions which are protected by SU-8 resist. Copper is electroformed by using copper sulphate solution at room temperature and by applying optimized current density of 10 mA/cm^2. The rate of copper deposition at this current density is found to be 0.2 µm/min. The negative resist is then stripped from the substrate surface using MCC's Remover PG and CF_4+O_2 plasma chemistry leaving behind the electroformed copper sacrificial layer. Next, once again 11 **µm** thick negative resist SU8 2010 is spin coated and patterned using the key structural layer mask. A 10

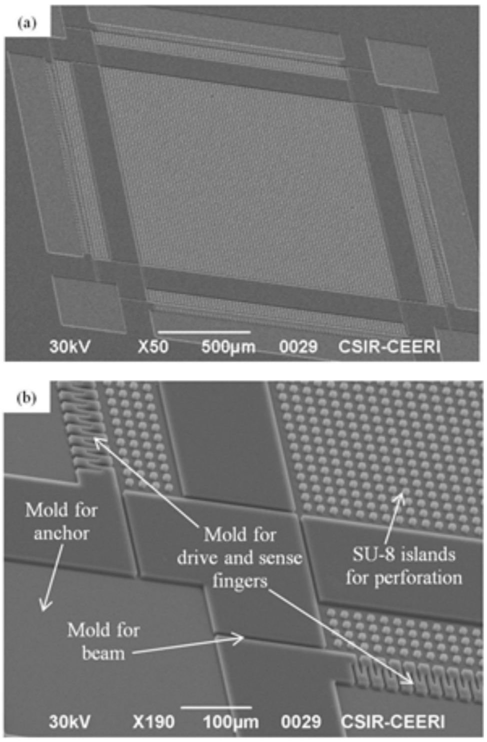

Figure 3: (a) SEM image of SU-8 mold for 2-DOF linear micro-gyroscope structure (b) Closer SEM image of SU-8 mold for anchor, beams, perforations, and fingers

µm thick Nickel is electroformed inside this thick resist mold. Nickel is electroformed by using nickel sulphamate solution at 48 °C and by applying optimized current density of 5 mA/cm^2. The rate of nickel deposition at this current density is found to be 0.067 µm/min. Thereafter, the negative resist is stripped using Remover PG and CF_4+O_2 plasma chemistry. The processed wafers are then diced using mechanical dicing saw. Finally, the copper sacrificial layer and seed layer are etched out selectively.

Fig. 6 shows the SEM images of fabricated 2-DOF linear nickel micro-gyroscope structure. For comparison, the images are taken at the same locations as in Fig. 3. It is clear from closer SEM image in Fig. 6(b) that structure is completely released, beams and other components have vertical side walls, and both drive and sense fingers including perforations in proof-mass are completely resolved.

Fig. 7 shows the SEM images of fabricated 4-DOF linear nickel micro-gyroscope structure. For comparison, the images are taken at the same locations as in Fig. 4. From the SEM image in Fig. 7(b), it is clear that the structure is completely released. Single U-turn and double U-turn beams are resolved with vertical side walls as is evident from Fig. 7(c) and Fig. 7(d). Besides, both drive fingers and sense split-fingers including perforations in proof-mass are also resolved as shown in Fig. 7(b) and Fig. 7(d).

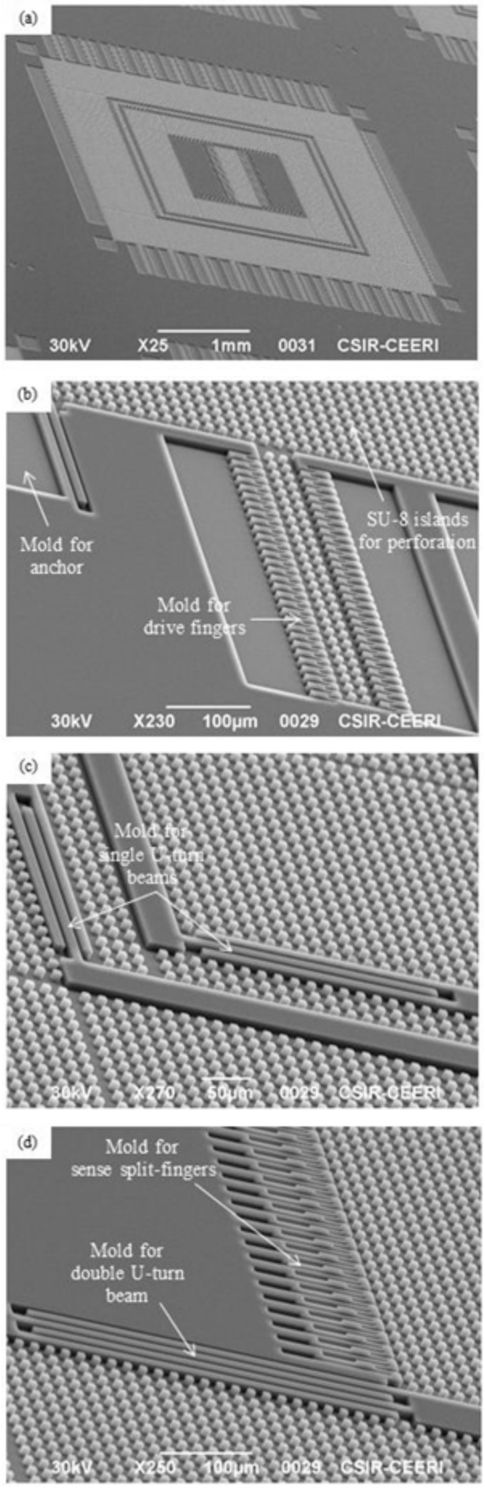

Figure 4: (a) SEM image of SU-8 mold for 4-DOF linear micro-gyroscope structure (b) Closer SEM image of SU-8 mold for anchor, perforations, and drive fingers (c) Closer SEM image of SU-8 mold for single U-turn beams (d) Closer SEM image of SU-8 mold for double U-turn beam and sense split-fingers

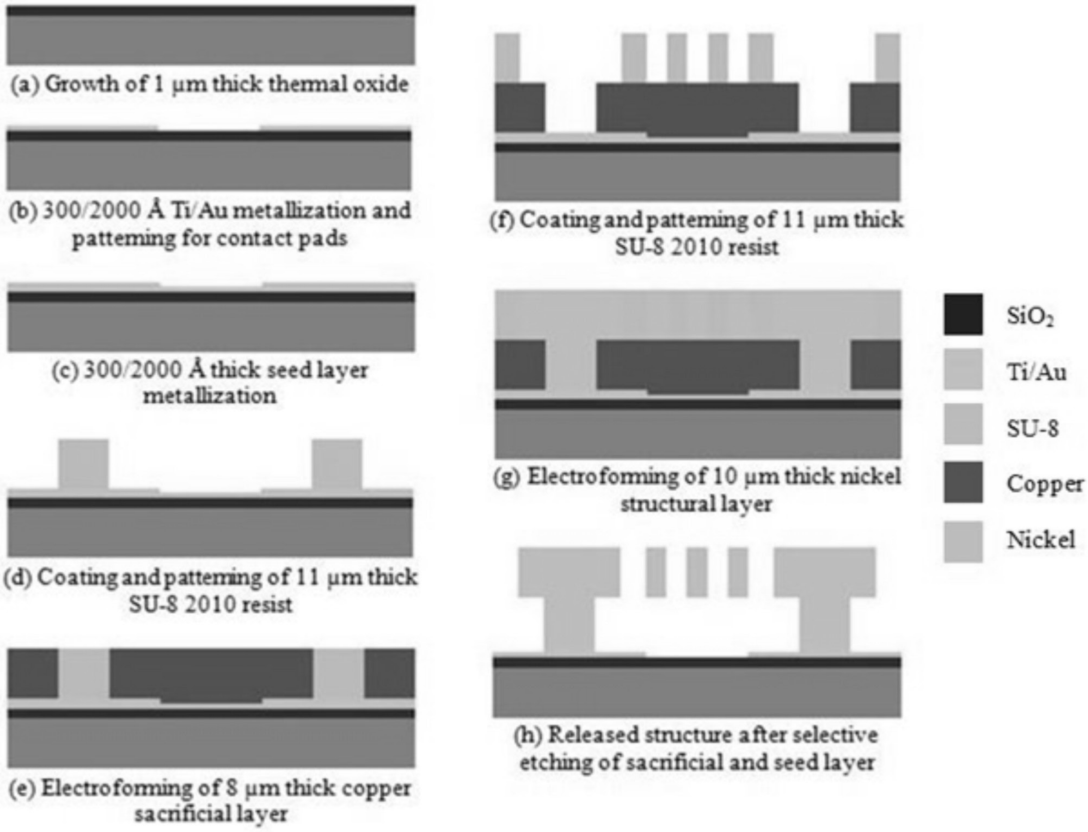

Figure 5: Fabrication steps in three mask UV-LIGA process

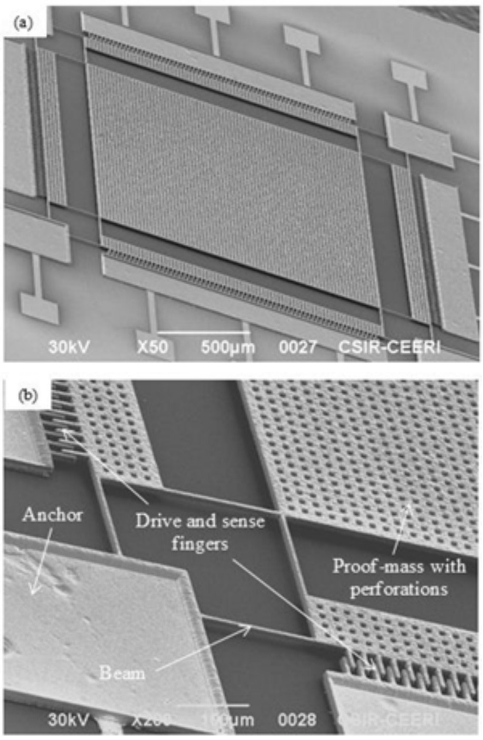

Figure 6: (a) SEM image of fabricated 2-DOF linear nickel micro-gyroscope structure (b) Closer SEM image of anchor, beams, perforations, and fingers of 2-DOF linear nickel micro-gyroscope

5 Conclusion

An optimized process for creating thick SU-8 mold and its application in the fabrication of UV-LIGA based micro-gyroscope structures is reported. Initial experiments are carried out on 4 inch silicon wafers with two different micro-gyroscope structures, a 2-DOF linear micro-gyroscope having minimum feature size of 5 µm and a 4-DOF linear micro-gyroscope having minimum feature size of 3 µm. The patterned SU-8 is examined using scanning electron microscopy (SEM) and is found to be completely resolved having near vertical side walls. Finally, the micro-gyroscope structures are successfully fabricated using SU-8 based UV-LIGA process having 10 µm thick nickel as the key structural layer.

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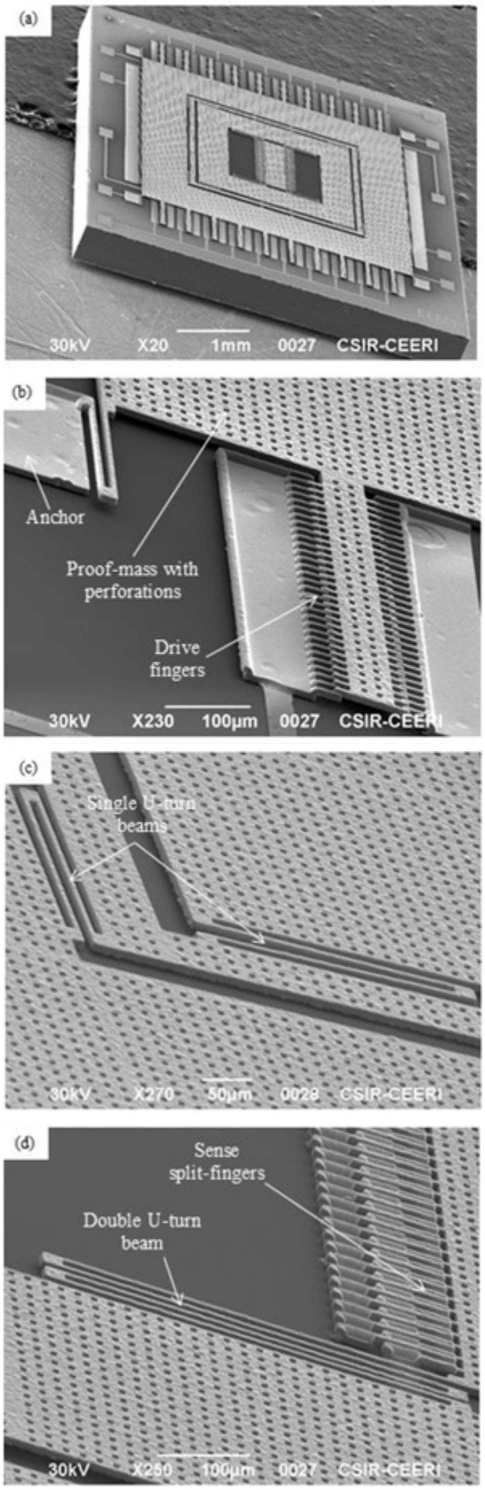

Figure 7: (a) SEM image of fabricated 4-DOF linear nickel micro-gyroscope structure (b) Closer SEM image of anchor, perforations, and drive fingers of 4-DOF linear nickel micro-gyroscope (c) Closer SEM image of single U-turn beams of 4-DOF linear nickel micro-gyroscope (d) Closer SEM image of double U-turn beams and sense split-fingers of 4-DOF linear nickel micro-gyroscope

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