Abstract

Gyroscopes sense angular speed of the body on which they are mounted. Traditional mechanical gyroscopes are big, bulky, expensive, and hence limited to a few applications. With the advent of Micro-Electro-Mechanical Systems (MEMS), the size and cost of gyroscopes have reduced by orders of magnitude, which has led to their deployment on systems that traditionally did not employ inertial units. Today, Internet of Moving Things (IoMT), automobiles, and consumer electronics gadgets such as cell phones, pads, laptops, gaming consoles, etc., use MEMS accelerometers and gyroscopes. Despite their commercial deployment and success, MEMS accelerometer and gyroscopes remain an active area of research and development because of their growing potential of applications and newer technologies for increasing their functionality and reducing their cost.

This work focuses on the complete design, fabrication, device level packaging, and characterization of two different types of MEMS gyroscopes—a dual mass electrostatic vibratory gyroscope and an electromagnetic ring gyroscope. We start by establishing a closed-form mathematical expression for gyroscope sensitivity relating to different design parameters. From the analysis, we present a case study on the effect of mismatch between the actuation frequency and the drive resonant frequency on the sensitivity of the gyroscope. Towards fabrication of MEMS electrostatic gyroscopes, we discuss several fabrication challenges involved in using the traditional SOI-on-glass method. Particularly, the alignment and residual stress issues are discussed in detail. Subsequently, we describe a modified SOI-on-glass fabrication method that successfully overcomes these issues. A novel hybrid wafer bonding method is presented in conjunction with the modified SOI-on-glass process. The proposed process flow is demonstrated by realizing several capacitive MEMS structures. Subsequently, the fabricated devices are characterized for their electrical and mechanical responses showing negligible process-induced stresses.

Further, we characterize some of the test-structures for their dynamic response under different ambient pressures. We report on the resonant frequency modulation of inertial MEMS structures due to squeeze film stiffness over a range of working pressures. We show with experimental measurements and analytical calculations how the pressure-dependent air springs (squeeze film stiffness) change the resonant frequency of an inertial MEMS structure by as much as five times. A detailed experimental methodology is discussed for finding static stiffness using AFM (Atomic Force Microscopy). Further, dynamic measurements are presented using a non-contact Laser Doppler Vibrometer under varying pressures. The experimental observations are compared with theoretical and FEM models.

Finally, we implement the proposed SOI-on-glass fabrication method to fabricate a dual mass, single-axis, folded tuning fork, electrostatic gyroscope. We rigorously characterize the gyroscope structures for their electrical and mechanical response at the die level. We have also developed a drive and sense pre-amplifier circuit for electrostatic gyroscopes. Thus-fabricated gyroscopes have been packaged, and characterized at the device level with rates of rotation from 1°/s to 35°/s, giving a rate sensitivity of 60 μV/$^\circ$/s with a linearity of 99.9%. In a parallel development, we have also fabricated an electromagnetic ring gyroscope that exploits the inherent symmetry of the ring structure and uses relatively low voltage to produce sufficient electromagnetic force for actuation. The electromagnetic ring gyroscope realized in this work requires very thin Al electrical tracks on a suspended ring structure of Si and on the suspensions for electromagnetic actuation and sensing. The process innovation implemented here is a single wafer process with a patented technique (arising from this work) for electromigration preventive layer. The gyroscope thus fabricated has been packaged and characterized giving a sensitivity of 0.04 μV/$^\circ$/s.

Although there is a fair amount of modelling and analysis presented in this thesis, the emphasis here is not on such analysis but on physical realization of the gyroscope. Consequently most of the innovations in this work are in fabrication processes and methods. The actual realization of an electrostatic gyroscope is a challenging task, particularly, in a university fab. We have been able to successfully fabricate and test two types of gyroscopes.

The entire fabrication and characterization reported in this work has been carried out at the National Nano Fabrication Centre, Micro Nano Characterization Facility of the Centre for Nano Science and Engineering, IISc.