# Position Paper: An Overview of MEMS Inertial Sensors

**Steve Tung**
**Department of Mechanical Engineering**
**University Of Arkansas, Fayetteville, Arkansas 72701**

Inertial sensors are widely used in advanced mechanical systems like guidance, robotics, and automobiles. In MEMS, research on inertial sensors has focused primarily on accelerometers and gyroscopes. Of the two, the accelerometers were developed first. Today, MEMS accelerometers enjoy a large commercial market and are considered to be one of the most successful micro sensors ever developed. MEMS gyroscopes, on the other hand, are a relatively new technology. Commercialization of low-grade devices has recently begun while intensive research is still being carried out in laboratories on high-grade devices.

MEMS accelerometers can be fabricated by using either surface or bulk micromachining. Extensive surface micromachining research in the last decade has resulted in the successful development of batch-fabricated accelerometers, which are widely used in the automobile industry as airbag sensors. These low-cost (~us$10 per unit) accelerometers, like the analog device adxl series, are typically comb-drive based and equipped with sophisticated on-chip signal conditioning electronics. The acceleration sensing in the comb-drive devices is carried out through the displacement of the polysilicon comb fingers. Due to the fabrication limitation of surface micromachining, the thickness and therefore the mass of the comb fingers is small (μm range), which imposes a severe limitation on the performance of the accelerometers. Typically, the accuracy of the commercially available surface-micromachined accelerometers is in the milli-g range, which is sufficient for impact sensing but does not satisfy the micro-g requirement of inertial navigation.

Bulk-micromachined accelerometers, on the other hand, can provide large proof mass and therefore higher accuracy. A typical bulk-micromachined accelerometer consists of a proof mass suspended on thin beams. Because of fabrication difficulties, the proof mass is usually not monolithically integrated with supporting electronics. As a result, bulk-micromachined accelerometers are typically more expensive than their surface-micromachined counterparts because of the additional manufacturing cost involved in packaging a separate ic chip along with the accelerometer. However, separating the accelerometer and the electronics allows the manufacturer to choose the best driving circuitry for the accelerometer, which is a great advantage in designing high-end accelerometers. Commercial companies like litton have been actively developing navigation-grade bulk-micromachined accelerometers for the military market. When packaged with gps electronics, these high-end accelerometers are expected to offer a complete solution to advanced navigation in the relatively low price range of us$3000 per unit.

Gyroscopes can be divided into three basic groups according to their performance: rate grade, tactical grade, and inertial grade. Conventional gyroscope technology offers all three gyroscope types, from the low-end spinning wheel gyro to the high-end ring laser gyro. So the obvious question is “why build another gyroscope?” The answer to this question is that conventional

gyroscopes are too bulky and power hungry to meet the requirements of future advanced systems like hand-held navigation and micro satellites. MEMS -based gyroscopes, on the other hand, offer a near-perfect solution because of their compact size, low-cost, and low power consumption. The majority of MEMS gyroscopes currently under development operates in a vibratory mode and measures the angular rate instead of the absolute angle. Their operational principle is based on the coupling of mechanical energy between a vibrating motor element and a sensor element through Coriolis acceleration. Like MEMS accelerometers, MEMS gyroscopes can also be fabricated by using either surface or bulk micromachining. A popular design for surface micromachined gyroscopes uses a comb-drive as both the motor and the sensor. This design leverages the fabrication technology developed for surface micromachined accelerometers and achieves a noise level of about $1^0/s/Hz^{1/2}$, which is accurate enough for automotive applications. However, just like the surface micromachined accelerometers, it also suffers from the 'low-mass' problem and is unlikely reach the level of $1^0/hr/Hz^{1/2}$ required for high-end military market.

The difficulty in overcoming the 'mass' factor in surface micromachined gyroscopes has led to the recent renewed interest in bulk micromachining. Among the main fabrication issues associated with bulk-micromachined gyroscopes, the most important ones are high aspect ratio etching, wafer bonding, and vacuum packaging. In the area of high aspect ratio etching, tremendous progress was made in recent years by companies like STS and Plasmatherm, who successfully developed ICP-based DRIE process chambers for the fast etching of deep and narrow trenches in single-crystal bulk silicon. This technology greatly simplifies the design of high-end gyroscopes by making the fabrication of high aspect ratio beams and proof mass possible. A good demonstration of this technology is the tactical-grade gyroscope developed by Litton. Another trend in bulk micromachined gyroscope that is gaining popularity is the utilization of SOI wafers. With their thick single-crystal device layers, SOI wafers provide the necessary substrates for large-mass mechanical structures, which are critical to gyroscope performance. Additionally, they also allow the possibility of integrating the mechanical structures of the gyroscope with the electronics, as in the case of surface micromachined gyroscope.

Fabrication of bulk-micromachined gyroscopes usually includes the bonding of several silicon wafers. Low temperature processes like anodic and eutectic bonding typically do not provide the necessary strong and thermally stable bonds required for high-end gyroscopes. Currently, the only suitable choice is fusion bonding, which is a high-temperature process ($\sim 1000^0$ Celsius). Since this process is incompatible with IC fabrication, another bonding option must be identified before integration of gyroscope and electronics can be realized.

Since MEMS gyroscopes operate in vibratory mode, a high quality factor is essential. In a laboratory environment, a quality factor of 1000 is usually high enough for a bulk-micromachined gyroscope to function. However, to achieve high performance, a quality factor of at least 10,000 is necessary. This requirement demonstrates the importance of vacuum packaging, which is probably the most overlooked area in gyroscope design. A good vacuum packaging scheme should ensure hermeticity over the designed operational temperature range of the gyroscope. To achieve this, a gettering material can be included inside the package to absorb any outgassing from the packaging materials.