Accelerometers have been amongst the first microsystem (MST/MEMS) products to be developed. However, reaching commercial success took from the seventies/eighties, when they were developed, until the nineties, with applications mainly in the automotive and avionics markets. Based on a very mature technology and high-volume, low cost manufacturing processes, accelerometers are now in an excellent position to successfully move into the harsh environment world (aerospace, geophysics, defence and industrial applications). Due to their robustness, stability and small size, inertial sensors (accelerometers and gyros) originally developed for drilling and later adapted to avionics, are penetrating new and very demanding markets. The case of MEMS accelerometers is a good example of how mature high-volume MST/MEMS products can enter new markets, and clearly illustrates what seems to be the most appropriate strategy to achieve commercial success with MST/MEMS devices in the near future.

High performances MEMS capacitive accelerometers that offer the required long-term stability and vibration rectification error characteristics are used in inertial guidance and navigation for aeronautic and defence applications. These products offer advanced functionalities and perform extremely well without degradation of specifications in rugged environments such as gun hard shocks with amplitudes higher than 20,000g, very aggressive vibrations or temperatures even higher than 150°C.

Two major markets currently determine the worldwide accelerometer business, independently of the technologies. Figure 2 shows the segmentation of these markets:

- The most important market in terms of total volume is the domain of movement monitoring and event detection, mainly driven by the automotive business (airbag, rollover applications) and by the low cost consumer business (hard disk drives, camera stabilisation, mobile phones...).

- The second market is the domain of measurement and control, mainly driven by the technology and dominated by the harsh environment (MEMS accelerometers for rugged environments), guidance (farming industry, robotic, avionic or defence...) and the tilt & stabilisation businesses.

Within this second area, various technologies are competing to...
gain market share from the traditional micro-mechanical products (quartz vibrating structures, micro-mechanical tilt sensors or geophones), with increasing demand from applications requiring inertial sensing, tilt and vibration sensing or seismic and vibration sensing products. New fields of opportunities exist today for those who can control the technology and provide a better price versus specifications ratio. The capacitive MEMS-based accelerometers (Figure 1) are ideal candidates to fulfil a large number of these requirements.

When referring to volumes and price, the conditions for the movement monitoring and event detection market are very different from the measurement and control market. For the automotive segment, production volumes are in 10’s of million of pieces sold at price levels of a few dollars. The volumes for the aeronautic and defence are much lower (10k to 100k) but the prices are in the range of 30$ to 150$. Based on our classification, five major application domains – each corresponding to a market opportunity - have been determined for the Measurement and Control Market. These are summarised in Table 1.

Recent developments have opened new opportunities in the field of seismic sensing or strong motion applications, requiring very low noise products. MEMS are slowly but surely replacing traditional geophones in various strategic applications and Colibrys is the key player in this domain.

A summary of the most important specifications for each generic application is given in Table 2. The analysis of these values shows that MEMS technologies offer sometimes little, if any, performance improvements with respect to classical technology, but they open up new opportunities as far as the most critical specifications - such as shock resistance, size or cost – are concerned.

MEMS accelerometer technology

For MEMS accelerometers, various detection schemes and physical technologies are available (piezoelectric, piezoresistive, capacitive, resonant, optical, magnetic, etc.). The bulk capacitive detection technique is the one offering the widest range of benefits for high quality sensors in the measurement and control market. Colibrys has developed a capacitive bulk micro machined Silicon sensor consisting of three Silicon wafers bonded together by fusion bonding. The middle plate contains a seismic mass attached at one end by a beam. Principle advantages of bulk capacitive technology are high precision, robustness, long life and low costs.

The high precision is guaranteed by:
• The homogeneity of materials used for the sensitive part of the sensor (Silicon and silicon oxide), which minimise all the mechanical constraints
• The use of monocrystalline silicon, a material with excellent mechanical proprieties, in particular for the spring of the inertial mass.
• A high temperature bonding process, which relays all the wafer assembly constraints and removes any surface contamination, especially that linked to OH groups.
• The elimination of the sticking effects and of the drifts of the electrostatic motor characteristics, due to a variation of the extraction voltages when using servo electronics.
• The use of a decoupling frame, which acts as mechanical filter that isolates the sensitive part of the device from the substrate to avoid feedback of the assembly constraints back to the sensing cell.

The robustness is guaranteed by:
• The basic material (monocrystalline Silicon), a very robust material with a point of rupture near that of the best steels (moreover, it doesn’t present plastic deformation effects at room temperature)
• The three layer technology, which offers natural stoppers that limit the spring deformation of the moving mass much before the fracture point
• The fact that the spring of the sensitive part acts as low pass mechanical filter and removes the high frequency components of the shocks (Aerobut tests on such sensors have established that elasticity of the beam combined with an adequate suspension of the sensitive cell enable the part to resist to shocks higher than 20,000g without significant degradation of the specified characteristics).

The lifetime of the products and achievement of cost targets are im-
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sured by:
• The choice of the Silicon technology and industrial approaches and associated processes which are well established and well controlled.
• The use of 4” to 6” silicon wafers linked to MEMS batch processing, ensuring potentially low unit costs.

Today, this technology is mature and the few companies that can accurately control the complex and demanding processes industrially are the ones that are manufacturing MEMS capacitive sensors. These products are enabling new applications, previously not considered feasible for technical and/or cost reasons. MEMS capacitive accelerometer specifications are of course dependant on the sensor itself, on the way the device is mounted on the substrate and finally on the electronic performance, which has a great influence on some specifications (stability, low noise, low power...).

All the major applications have their own and specific requirements and it is not easy, simply by analysing and comparing supplier datasheets, to select the most suitable product. Indeed, a large number of parameters are generally not even specified even though they are extremely important. The most critical ones are explained below.

Stability

Bias and scale factor stability are clearly the major parameters of interest for all applications and determine the grade of the accelerometer product. The intrinsic capability of MEMS capacitive technology is actually in the range of 1mg for a limited working range (Figure 3). To maintain this stability for a large working range, powerful closed-loop electronics are required. Sub mg stabilities are certainly achievable and developments are ongoing to combine the best practices and best know-how, from the design, assembly techniques and electronics point of view. The challenge is not only to develop such high end products, but also to be able to produce and sell them at a price suitable for the application (typically $150 in large quantities for high performance capacitive MEMS accelerometers).

Stability conditions can also be qualified on linearity, hysteresis or transverse sensitivity. The test methods and the definitions are well known (i.e. IEEE standards). However, the major effort needed to qualify and test a sensor for a high performance product is not yet common for MEMS devices. This still represents a major challenge when needing to assure the high performance of MEMS devices while keeping cost at an acceptable level.

Shock resistance

When speaking about shock resistance, one must really be careful about the definition. The survivability to a shock, without any consideration of the specifications must be clearly distinguished from the shock level (amplitude and duration) for which a product will see minimum or limited degradation of its specifications.

We distinguish in general three major categories of products:
• High-grade products (traditional micro-mechanical products) have a really low level of shock acceptance, generally lower than 500g.
• Standard MEMS products generally offer a shock resistance between 5000 and 10,000g. Note that these are short duration shocks (typ 0.2ms to 0.5ms) and have the specific form of a half sinus curve.
• The third category of products is compatible with gun hard shocks. These shocks are particularly long (typically 10ms) with typical amplitudes of 15,000 to 20,000g and generally combined with high frequency components.

The representation of performances vs. shock helps to better understand the distribution of these specifications and the challenges for further developments. Current results allow the manufacturing of standard MEMS products surviving gun hard shocks with offset shifts smaller than 15mg, 1 sigma (less than 0.05% of full scale) for a ±30g range. The challenge, presented in grey in Figure 4, is to develop a sensor with 0.001% performance, even if subject to 20,000g gun hardened shocks. This can be achieved via the design (high stability Silicon sensor), manufacturing techniques (fabrication of high quality sensors at low cost), assembly method (ad

Table 1 - Review of five major domains of application

Figure 5 - Gun hard shock profile (20'000g)
equate mounting combining decoupling and gun hard shock resistance, wire bonding, and choice of electronics (closed loop electronics) for the sensor.

Rectification error

The vibration rectification error (VRE) is the DC shift of bias in the presence of vibration. It is a direct consequence of non-linearity effects (geometric or dynamic). This shift of bias is particularly critical when the acceleration value is integrated over a period of time. This is generally the case in inertial navigation systems for defence and aeronautics. Intrinsic rectification error is largely determined by the design itself and/or by the process. Technical solutions exist to reduce this effect, either by selecting the products presenting the best geometrical symmetries or through a design which reduces the dynamic effects due to the non-linearity of the gas movements into the sensor cavity. All effects are generally cumulative and as example, rectification errors down to 60 mg/g can be achieved on 15g products. This value can be further reduced for larger g range products or with the utilisation of closed loop electronics.

Case study: gun hard shock resistance for applications in oil/gas exploration

Table 2 - Review of major application requirements

<table>
<thead>
<tr>
<th>Working range</th>
<th>Bias stability</th>
<th>Long term stability</th>
<th>Dynamic range</th>
<th>Noise</th>
<th>Linearity / RE</th>
<th>Environmental Shocks</th>
<th>Temperature</th>
<th>Size</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 to 100g</td>
<td>±1mg</td>
<td>2g to 15g</td>
<td>20 years</td>
<td>±105</td>
<td>20g/Hz</td>
<td>20,000g</td>
<td>±55°C</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>2g to 15g</td>
<td>±1mg</td>
<td>±2mg</td>
<td>15 years</td>
<td>±105</td>
<td>20g/Hz</td>
<td>1,000g</td>
<td>±45°C</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Up to 5g</td>
<td>±1mg</td>
<td>±5g</td>
<td>1 year</td>
<td>±105</td>
<td>50g/Hz</td>
<td>5,000g</td>
<td>150°C</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>2 to 15g</td>
<td>±1mg</td>
<td>±5g</td>
<td>5 years</td>
<td>±103</td>
<td>50g/Hz</td>
<td>5,000g</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>±1mg</td>
<td>±5g</td>
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</tbody>
</table>

JPSA (USA) has introduced the new IX-3000 machine, a Class 1 UV Excimer-based laser step and scan system. It is designed for a wide range of removal operations on different materials and components, such as microelectronics and microsystem machining, microvbia drilling, large-area patterning, manufacture of inkjet nozzle arrays, flat panel displays, wafer-scale processing, sensors, microfluidics, and many other applications, all with resolution down to 1 micron. According to JPSA, optical resolution, repeatability, and structural accuracies are at the sub-micron level, with repeatability in the order of 0.2 to 0.3 micron. The producer also states that the high-accuracy mask imaging system for large field of view (FOV) processing is flexible and suitable for development, prototyping, as well as for high-volume throughput.

248nm or 193nm UV wavelengths are standard features, but other different types of lasers are available to meet a variety of requirements. The IX-3000 is also surrounded by a cleanroom enclosure with HEPA filtration, with the filtration units mounted on the roof of the enclosure.

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Gun hard shocks with extreme values such as illustrated in Figure 5 are aggressive enough to break the Silicon sensor itself, the mounting of the sensor, and to impact the integrity of the wire bonding of any standard product. In such environments, a majority of the commercial MEMS products will simply break down or, if they survive the shock, will show large drift of bias and scale factor. A complete system has been developed that can survive such shock conditions and continue to measure very accurately with a limited impact on specifications within less than 1ms recovery time. The starting point of this development is the standard accelerometer MS8000 from Colibrys. Gun hardening was obtained by a careful design, taking the stress levels and the displacements of the different parts of the sensor (e.g. suspension of the spring mass, chip mounting) into consideration and keeping them within acceptable limits, well below the fracture stress. The gun hardening could be obtained without changing the devices characteristics such as stability, linearity and rectification. Further work is being done to develop the future generation of high range and high-grade products (sub mg stability) that can survive gun hard shocks without degradation of the specifications over 1mg.