The Advantages of Integrated MEMS to Enable the Internet of Moving Things
The availability of contextual information regarding motion and direction is transforming consumer device applications. Games, 3D user interfaces, contextual awareness, and navigation applications have increased the demand for MEMS sensors to deliver real-world, motion-aware applications that enrich the consumer experience. While these devices started in automotive and industrial applications, they have quickly become ubiquitous in gaming controllers, smartphones and tablets. That wave is now growing into an expanded Internet of Moving Things (IoMT) including smart wearables, sports equipment, and medical devices where the size and weight requirements have previously limited options for interfacing to these devices through motion sensing. Recently the need to meet size, power, and functionality requirements for these new markets has fueled a new wave of innovation in sensors. In fact, a new era of sensors is emerging where MEMS devices can provide designers with novel methods of user interaction and a self-aware quality that is compelling and driving new use cases in the Internet of Moving Things.

In Figure 1 you can see the evidence of this trend come to life with the steep reduction in accelerometer sensor size over the years. These reductions in size were largely achieved by optimizing existing designs and packaging. Minimum features have been pushed to physical limits and further advancement is now limited by the overhead of chip interconnectivity.

Another method for reduction in size involved combining multiple degrees of freedom (DoF). Accelerometer-gyroscope, accelerometer-magnetic sensor 6-axis products, and even 9-axis accel-gyro-mag products have come onto the market. The majority of these products, however, use the same MEMS processing at the wafer level. Integration and size reduction was accomplished by chip stacking of discrete sensor and CMOS die in assembly.

To truly accelerate the trend toward substantial reductions in size will require real innovations in the underlying fabrication technology. The next phase in MEMS sensor evolution will require integration of MEMS sensors with electronics in a competitive, monolithic process. Not only will this improve economy, performance, and functionality, it also will enable a chip-on-board (COB) approach not possible with solutions that require multiple die.

![Accelerometer MEMS size evolution](image.png)

**Figure 1:** Needs of consumer products are driving a rapid size evolution of MEMS Sensors.
Integrated MEMS

Integrating microelectromechanical structures (MEMS) with electronics is not new. Commercial production of a monolithic MEMS device was first achieved in the mid 1990’s. Despite the technical achievement, the market, in particular the consumer device market, preferred two-chip solutions, due to limitations in the original monolithic approach:

- **Area inefficiencies:** When MEMS were fabricated adjacent to CMOS, all the expense of processing unused area (i.e. MEMS processing before CMOS or vice-versa) was wasted and could not be recovered.
- **Lower yields:** The higher level of complexity in an integrated process lead to lower yields.
- **Advances in packaging:** Wafer thinning and stacking eroded the potential advantages integrated products were expected to achieve over two-chip solutions.

For these reasons, multi-chip solutions for accelerometers, gyroscopes, and pressure sensors have been the mainstay in the consumer market, but they are increasingly challenged to meet the size and cost reduction requirements without further sacrificing features and performance.

mCube is the first company to successfully bring to market an integrated MEMS+ASIC that does not suffer from these drawbacks. The mCube monolithic single-chip structural design offers:

- High yields
- Very efficient area usage
- Superior interconnectivity between MEMS and CMOS
- Significantly smaller footprint for devices with equivalent transducers
- Complete functionality at wafer level

A schematic cross-section is shown in Figure 2. Released MEMS structures are fabricated directly on top of standard CMOS, integrating the two more efficiently than in any previous commercial MEMS process.

![Figure 2](image_url): The mCube monolithic, single-chip platform, shown above in a schematic cross-section, integrates MEMS with CMOS more efficiently than in any other commercial MEMS product.
Process Overview

An overview of the major steps in the process is shown in Table 1.

The substrate for the MEMS process is a standard CMOS wafer. All processes to this step are standard foundry processes.

After patterning bond pads and release areas, a single crystal silicon wafer is bonded to the surface of the CMOS. The wafer is ground down to the target thickness.

Electrical connections are created between the MEMS and the underlying CMOS with specialized MEMS via. The MEMS structures are then patterned.

A cap is bonded over the MEMS structures at the wafer level. The MEMS is protected in a hermetic environment.

Table 1: The integrated MEMS process of the mCube accelerometer is efficient.

The process for the mCube accelerometer is able to overcome the historical drawbacks of an integrated MEMS process because of several key features:

- **Vertical integration**: MEMS structures are processed directly on top of CMOS. Unlike side-by-side or adjacent approaches, there are no significant keep-out rules or reserved processing areas that lead to an inefficient use of area.

- **Truly monolithic**: Because the MEMS features of the mCube accelerometer are defined lithographically, the alignment tolerance between MEMS and CMOS in the mCube accelerometer is 0.1 µm. The overhead is much less compared to MEMS wafer bonding, where the alignment tolerance of 3-5 µm must be accommodated in every feature.

- **Minimal size of interconnection**: The MEMS via in the mCube accelerometer is only 3 µm in diameter.

An example device is shown in Figure 3. The MEMS area has been decapped to show the underlying structure. The complete interface to the device, including all testing, is accomplished with eight bond pads. The process has several benefits that are particularly critical in the consumer markets of phones and wearables.

Figure 3: This SEM of the mCube accelerometer shows the MEMS structure monolithically integrated with the ASIC.
**Size**

Size reduction is achieved by significantly reducing the bond pads and their required overhead, (e.g. ESD protection) from the die real estate. This is accomplished with MEMS vias that ohmically connect the MEMS to the underlying CMOS directly. The vias shown in Figure 4 are only 3 µm in diameter. In a typical comparison such as that shown in Table 2, the integrated approach can have four times fewer bond pads than a two-chip approach.

**Figure 4:** These vias in a mCube device are directly connected to CMOS underneath.

<table>
<thead>
<tr>
<th>Approach</th>
<th>CMOS</th>
<th>MEMS</th>
<th>Total</th>
<th>No.</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Chip</td>
<td>23</td>
<td>9</td>
<td>32</td>
<td>90.1 x 10³ µm²</td>
<td></td>
</tr>
<tr>
<td>Integrated</td>
<td>8</td>
<td>–</td>
<td>8</td>
<td>22.7 x 10³ µm²</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2:** An integrated device can have four times fewer the number of bonded connections as a two chip approach for an accelerometer.

**Cost**

Figure 5 compares the cost vs. aggregate yield of a two-chip MEMS solution with an integrated device of comparable technology and performance. It shows that at lower yield, the two-chip approach has an advantage, primarily because of the ability to sort and pair known good MEMS with known good CMOS in assembly. In an integrated approach, if either the MEMS or the CMOS portion is defective, the entire product is lost. The integrated device, however, has a steeper reduction in cost owing to the smaller area in silicon for interconnecting the MEMS and CMOS, reduced test cost (one wafer load vs. two), and significantly lower assembly costs. At higher yields, an integrated device can have a lower total cost.

The advantage of bond pad savings for MEMS-CMOS interconnections becomes even more pronounced when considering devices with multiple degrees of freedom (DoF) such as a 6-axis accel-gyro combination.

**Figure 5:** The cost vs. yield curve is steeper for an integrated device.
Performance

In sensors that respond with a change in position (e.g. accelerometer, gyroscope, pressure), the preferred method of measuring that change in applications that are sensitive to power consumption is to measure a change in capacitance. Approaches that measure a change in resistance or frequency tend towards higher power consumption.

A second consideration in the performance of the device is the parasitic coupling of interfering signals. Whether the objective is to reduce the EMI cross section or shield from coupling to undesired signals like clock or communication, the MEMS via approach has a significant advantage over running long traces to bond wires between two chips. The intimate coupling of the MEMS to CMOS is inherently much easier to safeguard against interference.

Chip-on-Board

Up to this point, this paper has compared the advantages of an integrated device versus a multi-chip approach using attributes common to both. One particular benefit that is unique to the mCube monolithic, single-chip device is that it is a fully functional, self-contained product at the die level. Customers can consider using a chip-on-board (COB) assembly. The overhead of trying to do this with a multi-chip product would eliminate any potential advantage of this approach, particularly in the design of wearables and other space-constrained devices. mCube’s single-chip MEMS+ASIC design makes this unique form factor possible.

In addition, because it is not possible to know in advance which ASIC is married to which MEMS at a customer’s site, no wafer-level trimming can be performed prior to assembly with the multi-chip approach. In contrast, the monolithic, single-chip approach can test and trim many of the analog functions at the wafer level prior to shipping known good die because the MEMS and ASIC are a single chip. Chip ID numbers are also programmed into one-time programmable (OTP) memory, providing full traceability for both MEMS and ASIC processes back to the foundry.

Conclusion

The integrated monolithic, single-chip process and structural design enables mCube to ship the world’s smallest integrated accelerometer in volume. It can achieve this size without sacrificing performance or features. The savings from reduced size, lower testing costs, and lower assembly costs also enable this integrated approach to be very cost effective. While this approach has some advantages in the smartphone and gaming market, it offers an attractive path of continued innovation especially for designers of wearables and smart clothing.