High Volume MEMS Testing
Evolution, Challenges and the Future

Image from Wikipedia

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Common perceptions about MEMS testing

“MEMS testing is complex and really hard”

“MEMS testing is very expensive”

“There is a lack of MEMS test system suppliers”

“Cost of capital equipment for high-volume MEMS testing is a major barrier to market entry”

“MEMS testing is a way to establish competitive advantage”

“MEMS testing is not value-added, but a necessary evil”
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Introduction

• High volume MEMS testing, including **calibration and verification** of sensor functions, has long been considered **costly, complex** and a **major barrier to scale**

• Rapid adoption and commoditization of sensors in consumer electronics (i.e. smartphones) has driven **major innovations** in MEMS production test equipment and technology.

• There are readily available solutions for high-volume testing of **motion sensors, pressure sensors, humidity sensors, proximity sensors, light sensors, microphones and combo-solutions**

• Multiple vendors are providing competitive **turnkey systems**, either as a one-stop-shop or through partnerships

• This presentation will discuss some of the **key lessons** learned in the **evolution of MEMS testing**, what the **current challenges** are and the implications of a **futuristic trillion sensor market**
The variety of MEMS and sensors available for consumer electronics has exploded in recent years.

**Smart Sensor Development in Consumer Electronics**

- **2005**
  - Accelerometer (Samsung SCH-S310 possibly 1st application)
  - Proximity Ambient Light (Original iPhone)

- **2006**
  - Magnetometer (iPhone3)

- **2007**
  - Gyroscope (iPhone4)

- **2008**
  - Accelerometer/Magneto combo

- **2009**
  - Pressure/Barometer (Samsung Galaxy)
  - Temperature Humidity (Samsung Galaxy)

- **2010**
  - Accelerometer/Gyro combo
  - High performance MEMS microphone (iPhone4)
  - Heart rate (Samsung Galaxy)

- **2011**
  - Magnetometer (iPhone3)

- **2012**
  - Fingerprint (iPhone 5s 1st major use)
  - Hall Effect (Samsung Galaxy)
  - Temperature Humidity (Samsung Galaxy)

- **2013**
  - Pressure/Barometer (Samsung Galaxy)
  - Heart rate (Samsung Galaxy)

- **2014**
  - RGB, proximity, gesture (Samsung Galaxy)
  - 9-axis motion combo

- **2015+**
  - Emerging tech: Force, Pulse, Gas/chemical, UV, Thermal imaging, Etc.
  - Apple iPhone introduced with 3 sensors
  - Samsung Galaxy has more than 10 sensors, most of any phone on market

**Sources:**
The volume of MEMS and sensors in consumer electronics has also grown rapidly.

Smartphones and tablets account for the majority of sensor volume today; Wearables are positioned to become a much larger source of volume going forward.

![Global MEMS Unit Shipments (Consumer Electronics)](image)

**Sources:** Consumer & Mobile MEMS Market Tracker, IHS, April 2014
In 2015, FitBit went public, Xiaomi’s fitness band hit 1M units in Q1 and the Apple Watch was released.

Wearables are not just for technophiles and early adopters as proven by triple digit growth from end-users and providers.

A total of 27.4M units were shipped in Q4, 2015, which is a 171.6% increase from Q4, 2014.

FitBit is the market leader and address multiple market segments, from the casual exercisers to serious athletes.

Apple released its Apple Watch in 2015, but will not report unit sales on this new segment. Expectations are high for the next-generation Watch platforms (HealthKit, ResearchKit, WatchKit, and watchOS 2) and connectivity capabilities.

Xiaomi is continuing their focus on inexpensive fitness trackers with unit prices as low as $11.

Source: “The Worldwide Wearables Market Leaps 126.9% in the Fourth Quarter and 171.6% in 2015, According to IDC”, IDC, 2016
High-volume test systems are available for many MEMS devices and the list is growing with device volumes

• **Inertial Sensors**
  – High g accelerometer
  – Low g accelerometer
  – Combo sensor up to 9 DOF
  – Gyroscopes with constant yaw rate
  – Gyroscopes with sinusoidal stimulus
  – Magnetic sensors and compass

• **Pressure sensor**
  – Ambient Pressure (0 to 1.2 Bar)
  – Higher Pressure (< 14 Bar)

• **Optical Sensors**
  – Ambient Light
  – RGB
  – UV Sensors

• **Humidity Sensors**
  – Relative Humidity

• **Proximity Sensors**

• **Oscillators**

• **Microphones**

• **Temperature Sensors**
  – Consumer/industrial (-20 to 85°C)
  – Automotive (-40 to 150°C)

Despite the proliferation of MEMS and billions of units shipped per year, MEMS testing is still chronically lacking testing standards
I Introduction to High Volume MEMS Testing

II High Volume MEMS Test | Evolution

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IV High-Volume MEMS Test | The Future
MEMS testing has evolved over time, largely following the evolution of MEMS devices and package standardization.

**Level 1 - Custom MEMS**
- Custom, custom, custom
- Large MEMS die, mostly packaged in non-IC standard packages with analog output
- Low to medium production volumes
- Custom test systems
- Functionality over cost
- Mix of manual and semi-automated processes

*Test system suppliers: none*

**Level 2 - Standard Products**
- Packages approaching IC standards
- Volumes ramping up
- Custom test systems
- Functionality over cost, due to lack of viable options
- Semi-automated and fully-automated systems

*Test system suppliers: a few (mostly system integrators)*

**Level 3 - Commodityzied**
- IC standard packages; small footprint and leadless
- High-volumes, billions of units per year
- Standard test systems from multiple vendors
- Fully-automated systems and high parallelism

*Test system suppliers: multiple (turnkey and modules)*

Images from SensoNor, and Technology Review
From bench-top, to high-volume to consigning test systems to subcons and assembly houses that provide testing as a service

Custom Bench Top-Systems

High-Volume Manufacturing Line

Images from from Solidus and SPEA, Webpage cut outs from Amkor and ISE websites
MEMS high volume test solutions are now available as full turnkey-systems, from single companies and partnerships.
Here are some of the innovative test developments and solutions for consumer applications

- **Conductive Heating/Cooling**
  - Thermoelectric conductive heating/cooling
  - Ramp up and down in 10s of seconds
  - Traditional chamber type systems need hours
  - Allows one-time insertion testing

- **Modular Test Systems**
  - Dedicated systems are risky; millions of dollars tied up in machines that can only test one type of sensor
  - Automation companies are coming up with multi-use handlers with exchangeable MEMS test stimuli

- **Wafer Input Stage**
  - Automatic handling of CSP is challenging
  - Automation companies are reportedly working on wafer input test systems

- **Quick Change**
  - Flexible handler solutions allow product changeover to take minutes, not hours
  - FPGA product configuration

Images from Wikipedia and mCube
Test stimuli cells are replaceable in the field, allowing for example, changing from testing motion sensors to pressure sensors. Tester is embedded in the handler to minimize footprint.

Handling + Testing + MEMS Stimuli from SPEA

Test stimuli cells are replaceable in the field, allowing for example, changing from testing motion sensors to pressure sensors. Tester is embedded in the handler to minimize footprint.
Modular turnkey test system example | In carriers

Strip-like device carrier for singulated devices reduce handling time since the devices are tested in the carrier. Combines the advantage of single device test and handling of strips.

Handling + Testing + MEMS Stimuli from Xcerra
(Multitest and LTX Credence)

Images from Multitest (Xcerra)
Return on Investment (ROI) and test unit cost calculation

Low profit margin on MEMS is a significant barrier to entry and to purchase high-volume test systems. Test cost per unit (not including labor, consumables and overhead) is sub-cents

<table>
<thead>
<tr>
<th>Item</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost Per System</td>
<td>$1,500,000</td>
</tr>
<tr>
<td>ASP, margin</td>
<td>$0.10</td>
</tr>
<tr>
<td>ROI</td>
<td>&gt;15M yielded units</td>
</tr>
</tbody>
</table>

Test Unit Cost

<table>
<thead>
<tr>
<th>Item</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost Per System</td>
<td>$1,500,000</td>
</tr>
<tr>
<td>Throughput, UPH</td>
<td>10,000</td>
</tr>
<tr>
<td>Utilization</td>
<td>85%</td>
</tr>
<tr>
<td>Test Yield</td>
<td>98%</td>
</tr>
<tr>
<td>Good Units per Year</td>
<td>~56M</td>
</tr>
<tr>
<td>Depreciation</td>
<td>5 years</td>
</tr>
<tr>
<td>Unit Test Cost</td>
<td>$0.00536</td>
</tr>
</tbody>
</table>

If MEMS ASP is $0.20, test unit cost is **2.7%***

* Test unit cost only includes capital equipment and not labor, consumables, overhead etc.
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There are four identified megatrends for MEMS, but what are the test implications?
MEMS megatrends | #1 Commoditization

Commoditization of MEMS

Product Life Cycle

- Genesis
- Custom
- Product
- Commodity
- Original iPhone (2007)

Further growth depends on new applications

Test Implications

- **Lower Cost** – Lower ASP translates to cost optimization throughout the supply-chain, including test; yield pareto, test time, test points, parallelism, one-pass calibration etc.

- **Smaller Size** – Smartphone OEMs are driving smaller footprint and lower height, which is pushing the boundaries for automated MEMS component handling and testing

- **Lower Power** – Lower power does not have test implications per se, but there could be future implications for testing integrated devices with energy harvesting capabilities

- **Standardization** – Testing provides limited if any competitive advantage. Multiple equipment manufacturers with flexible test solutions. Outsourcing of testing to service providers, often on consigned equipment

Further growth depends on new applications
**Integration of Sensors into System-on-a-Chip (SoC)**

### System Integration

#### Motion Sensor Integration (Example)

- **Level of Integration**
  - ACC
  - MAG
  - GYR
  - BARO
  - IMU
  - MAG
  - ENV
- **Time**
  - 9-axis
  - 9-axis + 3
  - MCU

#### Sensor Hub Integration (Example)

- **FLASH / SRAM / ROM**
- **ICM-30630**
- **Cortex M0**
- **Motion Controller**
- **ICM-30630**
- **Cortex M0**

### Test Implications

- **Combo Sensors** – Increased integration of multiple sensors are on the rise, but mostly segregated into “motion combos” and “environmental combos”

- **Sensor Hubs** – Several sensor companies have already integrated a dedicated low-power MCU with sensors. This adds test requirements for digital and possibly mixed-signal testing

- **Advanced Packaging** – Heterogeneous integration, TSVs, WLCSP, 2.5D/3D are all packaging concepts that will allow increased functionality in a smaller footprint. The test implications (and failure modes) are not entirely clear yet

- **Test Cost** – Additional functions and features will require more testing and longer test times

Images from Technische Universitat, Muenchen and Invensense
MEMS and CMOS Compatibility

**Wafer Bonding Example (InvenSense)**

**InvenSense Fabrication Process**

CMOS-MEMS Structure

**TSV Example (Mcube)**

Images from InvenSense and Mcube

**Test Implications**

CMOS process compatibility does not have any direct impacts on final testing (wafer probe for sure), but there are some indirect effects!

- **Smaller Size** – Increasingly smaller package sizes is challenging the interface between the DUT and tester, including pitch between pogo pins used for contacting.

- **WLCSP** – This is huge. Up to now, no test system can take wafer at the input stage. It has been limited to singulated components and leadframe strips. However, automation companies are working on this!

- **Package Flexibility** – Single die integration allows smaller die that can fit in a range of packages. This has implications for test systems that are flexible and can be tooled for various package sizes.
MEMS Process Standardization along Multiple Platforms

MEMS Standard Process Platform

MEMS Standard Module Processing Example (Tronics)

<table>
<thead>
<tr>
<th>Platform</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corto</td>
<td>High performance inertial sensors</td>
</tr>
<tr>
<td>M&amp;NEMS</td>
<td>Multi-axis sensors</td>
</tr>
<tr>
<td>M&amp;NEMS</td>
<td>Ultra miniaturized</td>
</tr>
<tr>
<td>M&amp;NEMS</td>
<td>Life Sciences</td>
</tr>
<tr>
<td>M&amp;NEMS</td>
<td>Radio Frequency components</td>
</tr>
<tr>
<td>M&amp;NEMS</td>
<td>Optical components</td>
</tr>
<tr>
<td>M&amp;NEMS</td>
<td>Pressure sensors &amp; micro-fluidic systems</td>
</tr>
</tbody>
</table>

Test Implications

Standardization of MEMS processing does not have any direct impacts on final testing, but there are some indirect effects!

- **Time to Market** – The ultimate goal is to have PDKs and standard platforms for MEMS. There will likely be multiple platforms and PDKs might never be as well defined as for CMOS, but the time to market for MEMS will likely decrease. This will put pressure on scaling up test capacity and test systems fast.

- **Turnkey MEMS** – MEMS process standardization is one more step towards foundries being able to provide complete turnkey MEMS, including packaging, testing and drop-shipping to customers. Increased outsourcing of testing is also likely. This has already started with major assembly houses now starting to provide MEMS test services.
Test units and test systems have different requirements

Designing the optimal test system for a given applications is an exercise in trade-offs and finding the right balance between cost, speed and performance

### Unit Test Requirements

**Key Parameters**
- **Cost** – fail only bad parts
- **Speed** – minimize test time
- **Quality** – maximize test coverage
- **Calibration and Verification** – compensate sensors under real-world application conditions
- **Accuracy** – accurate calibration of sensor functions
- **Final Test** – verify fab and assembly processes
- **Stability** – test under stable conditions

### Test System Requirements

**Key Parameters**
- **Cost** – minimize cost per system (capital cost)
- **Throughput** – maximize UPH
- **Flexibility** – ability to test different products in the same system
- **Scalability** – simple and cost-efficient to scale
- **Performance** – accurate control and measure physical stimuli for MEMS testing. Low drift over time and test isolation from the environment, for example, isolate gyro testing from external vibrations

Images from TESEC and Bosch Sensortec
Integration of multiple sensor functions in a package might help minimize the footprint, but is posing major challenges to cost-efficient testing.
Minimizing test cost is a major focus and pursued by higher parallelism, reduced test time, faster handling, improved interface and optimized test software.
MEMS high-volume testing has largely been solved!

But Wait... There's More!

How are we going to support testing a trillion sensors?
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How to support testing of 1T sensors?

Trillion sensor “movement” predicting trillions of sensors, but have not yet defined a product roadmap for how to get there...

Source: “A trillion sensors is the equivalent of 150 sensors per human on earth “, SPB-Global, 2015
1T sensors? Is that even remotely possible?

1T is a huge number. What else is approaching 1 Trillion... Oh, right, semiconductors...
IC Insights forecasts 1,024.5 billion units by 2017 at 8.2% annual unit growth

Sources: “Semiconductor Unit Shipments To Exceed One Trillion Devices in 2017”, IC Insights, 2015
So, what about MEMS?

So, the total MEMS market in 2015 is a $10B business. IC Insights predicts continued growth and new applications to stop price erosion. 1T units? Not any time soon…

Source: “MEMS market growth rate turns up”, EE Times, 2014
What would it take to test 1T sensors?

We will play along and do a theoretical calculation based on leading edge test systems in the market today (numbers are based on the calculation on slide 16)

**Total Investment Needed to Test 1T Sensors**

<table>
<thead>
<tr>
<th>Item</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>$1,000,000,000,000</td>
</tr>
<tr>
<td>Throughput, UPH</td>
<td>10,000</td>
</tr>
<tr>
<td>Good Units Per Year</td>
<td>56,000,000</td>
</tr>
<tr>
<td>Investment</td>
<td>$26,785,714,286</td>
</tr>
<tr>
<td>Number of Systems</td>
<td>17,857</td>
</tr>
</tbody>
</table>

We need $26B to procure 17,857 test systems to test 1T sensors!
Summary | Common perceptions about MEMS testing

“MEMS testing is complex and really hard” ×
“MEMS testing is very expensive” × +
“There is a lack of MEMS test system suppliers” ×
“Cost of capital equipment for High-volume MEMS testing is a major barrier to market entry” +
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• Published over 9,800 stories, interviews, and articles and have reviewed more than 26,000 patents and patent applications
• Services include:
  – **Strategic Planning** (focus and positioning, marketplace perception, competitive analysis, roadmap development)
  – **Market Research and Intelligence** (technology scouting and assessment, system and components teardowns, patent/IP analysis)
  – **Event Organization and Management** (organize 4-5 events and sponsor 20-25 events per year)
  – **Marketing and Advertising** (brand building, lead generation)
  – **Content development** (whitepapers, presentations, reports)
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AUTOMOTIVE SENSORS AND ELECTRONICS EXPO 2016
DETROIT • MICHIGAN
JUNE 15-16, 2016

MEMS Testing & Reliability 2016
WORKSHOP AND EXHIBITION
SANTA CLARA • CALIFORNIA
AUGUST 2 • 2016

MEMS MANUFACTURING 2016
SANTA CLARA, CALIFORNIA • AUGUST 3-4, 2016
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