CMOS-MEMS for the next generation of “Combo” Sensors

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### Agenda

1. **InvenSense Overview**
2. **Challenges with MEMS Development**
3. **Evolving MEMS Platforms**
4. **“Combo” Sensors and MEMS SOC approach**
InvenSense at a Glance: Fabless MEMS Leader for Motion Sensing

**Selling Into Multiple High Growth End Markets**

- Mobile
- Gaming & Other

**Projected 2.8 Billion Unit Servable Market**

**Established Fabless Supply Chain**

- 200 MM Units Shipped
- CMOS/MEMS Manufacturing & Packaging Partners
- In-House Test & Calibration Facilities

**FY12 YTD Revenue Breakdown**

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<th>($) in Millions</th>
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**140+ Customers**

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- Selling Into Multiple High Growth End Markets

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**140+ Customers**

- Nintendo
- Samsung
- HTC
- LG
- Rim
- ZTE
- Panasonic
- Sony Ericsson
- Acer
- Sharp
- Huawei
- Pantech
- Roku

1 Represents 2015E projected metrics per iSuppli, Yole and Techno Systems Research.

2 Note: Fiscal year ends Sunday closest to March 31.

3 As of April 1, 2012. Based on Non-GAAP net income, which excludes change in fair value of warrant liabilities.
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MEMS vs. CMOS SOC

“Micro-Electrical-Mechanical-Systems”

- Combination of mechanical and electrical components which provide a completely functional system

We can develop multi-million gate ASIC “Systems”, why is MEMS so challenging?

- In CMOS, a large body of proven IP exists along with proven “SOC” flows which allow rapid development of complex systems. This is the accepted standard for product development. People expect this level of functionality, developed in rapid time frames, and provided at low cost.
The MEMS Challenge

No Standard MEMS Processes

- Optimized for specific functions. Not Versatile. Once frozen, needs to quickly ramp to high volume

Process are not stable prior to MEMS design

- Sensors are designed jointly with these specialized processes

MEMS is not stable prior to CMOS design

- Sensor circuits customized to each sensor

There is no standard platform or proven IP to design these “Systems”
Traditional MEMS Development

Process, mechanical structures, CMOS circuits all need to be developed in parallel with “System” design.
Development Challenges

| Process Development | • “One product - one process” increases barrier to entry  
|                     | • Finding foundries capable and willing to develop new process |
| Product Development | • Difficult to develop a product if the process is not stable  
|                     | • Optimizing both design and process simultaneously  
|                     | • Need for fast design iterations to keep up with market |
| Production          | • Over 50% of costs traditionally are in package and test  
|                     | • Need to quickly establish high yield and quality  
|                     | • Consumer products require ability to rapidly scale capacity |

Expertise and focus are required in all three areas, which can dilute resources.
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MEMS Process Generations

**Gen 1**
- **Bulk silicon micromachining**
- Breakthrough: anisotropic etching of silicon
- Challenges: non-active structure, limited use

**Gen 2**
- **Thin–film surface micromachining**
- Breakthrough, release of this films by sacrificial HF etching
- Challenges: limited structural material, non-optimized CMOS-MEMS process,

**Gen 3**
- **DRIE and Wafer-Level Encapsulation**
- Breakthrough: Bosch process, wafer level bonding
- Challenges: two chip solution, high cost of package and test

**Gen 4**
- **Nasiri-Fabrication CMOS-MEMS Integration**
- Breakthrough: Wafer level CMOS-MEMS integration
CMOS-MEMS with Surface Micromachining

- Developed by UC Berkeley, MIT, Wisconsin University and Sandia National Labs - Promised to become the next revolution
  - Funding by DARPA and NSF as the next emerging technology
- 1st commercial success mid 90s for automotive airbags, reduced unit prices from ~$7 to $2 by Motorola and ADI
- Premise
  - Deposited layers such as polysilicon gates used as structural material
  - Integration of MEMS and CMOS to reduce cost and size and single chip

UC Berkeley Accel development

Fig. 5: Photograph of a monolithic three-axis polysilicon surface micromachined accelerometer with integrated signal-delta readout and control circuit [40].

ADI Accel development

Fig. 3: A fully integrated, surface micromachined 2g dual axis accelerometer, ADXL202 available from Analog Devices.
Limited Success of Early CMOS-MEMS

- Major investment required to establish the process
  - Expensive poly reactors, licenses

- Fabrication and Packaging Challenges
  - “Sticktion”, particles
  - No flexibility, portability, or a viable evolution path

- Market adoption limited
  - Airbag, Inkjet

- Current products using Surface micromachining
  - Accel, Gyro, Microphone
  - Separate CMOS and MEMS
Addressed many of the problems with CMOS-MEMS integration

- Completely independent MEMS and CMOS processes
- Use die to die bonding and SIP for fully system

With some drawbacks

- SIP is more expensive than single die
- High number of wire bonds cause difficulties for “combo” sensor integration
- High parasitics and difficult to shield sensitive signals

SIP gets very complex when integrating multiple sensors

Traditional Approaches

- System in package
- Use of wire bonding between MEMS and ASIC
- Produced in high volume (by ST, Bosch, Analog Devices, Freescale…)

Source: System Plus consulting
MEMS processes are becoming more capable and multi-purpose
- People are moving away from optimizing a process for each product

New approaches to CMOS-MEMS integration
- Key is to be able to use a standard CMOS process with no modification

Several use the CMOS metal for MEMS structures
- CMU, Akustica, Baolab, Cavendish Kinetics

MEMS on top of CMOS
- WiSpry

Bonding a MEMS wafer to CMOS
- InvenSense, TSMC

Ideal Platform: A versatile MEMS process which can be easily combined with standard CMOS processes.
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Increasing Sensors in Smart Phones

~60% Attach Rate for High End SM-Phones With 9-axis Motion Interface

1st SM-Phone With 3-axis Accel 2006
• UI’s have evolved from key entry, to touch, motion, and now people are talking about “contextual awareness”
• understand the “context” under which a device is being used.
• Availability of low cost sensors help drive this paradigm shift
• Expanding variety of MEMS sensors being developed
• Examples: light, proximity, inertial, audio, ultra-sonic, temperature, pressure, humidity, and chemical sensing

As the number of sensors included in a product increases, there is more opportunity to aggregate these sensors into a few products
“We believe that the market for discrete sensors will begin to decline, but the growth for combo solutions will be huge. Though currently less than $100 million niche, we expect combos to be a $1.7 billion opportunity by 2017”*

*I-Micronews: 2012 Status of MEMS Industry, Yole Devel. And MIG, Abstract*
Evolution of Motion Sensors to MotionTracking

Motion Sensors

- MPU-6050
  - 6-Axis
  - 4x4x0.9mm
- MPU-9250
  - 9-Axis
  - 3x3x1mm
- 3-axis compass
  - X/Y: 3x3x1mm
  - Z: 10x1.4x3.9
- 3-axis Accel
  - 4x4x1.45 mm
- 2-axis Gyro
  - 6x6x1.4 mm

Integrated MotionTracking

- MPU-6500
  - 6-Axis
  - 3x3x0.9 mm
- MPU-0250
  - 9-Axis
  - 3x3x1 mm

2002-2005
- 1-axis Gyro
  - 7x12x2.6 mm
- 3-axis Compass
  - 5x5x1.8 mm
- 3-axis Accel
  - 4x4x1.45 mm
- 3-axis compass
  - XY: 3x3x1mm
  - Z: 10x1.4x3.9
- 3-axis Accel
  - 3x3x1 mm

2006-2009
- 2-axis gyro
  - 6x6x1.4 mm
- 2-axis Gyro
  - 4x5x1.2 mm
- 3-axis Accel
  - 3x3x0.7 mm
- 3-axis compass
  - 2x2x0.7 mm

2010
- 2-axis Gyro
  - 4x4x0.9 mm
- 3-axis Accel
  - 3x3x1 mm

2011
- 3-axis Gyro
  - 4x4x0.9 mm

2012
Advantages of “Combo” Sensor Integration

**Cost**
- Smaller die due to shared circuits

**Size**
- Single die package smaller than SIP packages

**Power**
- Share bias, digital current across multiple sensors

**Performance**
- Low parasitic connections
- Leverage a “system” approach with multiple sensors
Example of “Combo” Sensor Integration

### Integrated 6-axis Solution (MPU-6500 model)

- **Package Size**
  - 3x3x0.9mm, single die
  - 5x4x1.1mm, 4 die

- **Components**
  - 3-Axis Accelerometer
  - 3-Axis Gyroscope
  - Digital Motion Processing (DMP) Engine

- **Sensor Fusion**
  - Single I2C or SPI output
  - Single 6-axis Sensor Fusion

- **Cost**
  - Low cost QFN

### SIP 6-axis Solution

- **Package Size**
  - 5x4x1.1mm, 4 die

- **Components**
  - Accelerometer
  - 3-Axis Gyroscope

- **Sensor Fusion**
  - Two separate I2C outputs

- **Cost**
  - High cost Multi-chip LGA

Source: STMicro company website and “MEMS on Silicon” presentation, Sept 29, 2011.
Note: Competing 6-axis solution statistics are for STMicro’s LSM330DL model.
• Motion sensing MEMS are rapidly adopting an integration or “Combo” sensor roadmap to reduce size and cost
• This leverages a single common package and production test
• Can also leverage many common CMOS blocks such as:
  1. Bias, voltage reference, temp sensor for compensations
  2. Digital interface and FIFO to locally store data
  3. NVM for storing calibration data
  4. Digital state machine or processing for “smart” interrupts or higher level sensor outputs
  5. Potentially ADC conversion and DSP circuits
Even a simple feature such as a digital interface adds extra circuitry and cost which can be shared as additional sensors are integrated.
Hierarchy for Mobile Sensor Integration

- **Individual sensors**
  - Lowest level, but can provide built in intelligence to lower system power and embed sensor expertise.
  - Low power consumption, so many sensors can stay active for long periods of time.

- **Sensor Hub**
  - Aggregates sensor inputs, can provide some information processing to determine if the AP should be woken up.
  - Uses less power than the AP, signal processing can be shared across all sensors.

- **Application Processor**
  - Used for the “heavy lifting” in processing the sensor data and enabling applications.
  - Uses the most power when active. Needs to be able to sleep for long periods of time when the system is idle to save power.

**MEMS SOC approach:** sensors and hub can be integrated into a single product.
One of the biggest advantages of CMOS-MEMS integration is the large number of interconnects possible between the MEMS structures and the CMOS circuits.

This is a significant benefit for any “array” style sensor.

Examples:

- IR sensors for imaging
- Ultrasonic sensors for imaging or position
- Chemical sensors for a broad range of different elements
The Availability of CMOS-MEMS Platforms

• Foundries now offer CMOS-MEMS Platforms
  • Greatly simplifies MEMS product development
  • Stable Process which can quickly ramp to high volume

• Companies can now focus all their resources on the MEMS structures and overall system design

This should significantly reduce the challenges for new MEMS start-ups and help create a wave of new, innovative sensors.
MEMS Development Roadmap

MEMS Process
• Several commercially successful products
• One Process, one Product – Very Challenging model, few successes

MEMS Platforms
• Multiple MEMS products on a single MEMS platform
• One Process, Multiple Products – Better, but hard to increase functionality

MEMS SOC
• Multiple sensors integrated in single product
• One Product, Multiple Sensors – Best, maintain ASP by increasing functionality

MEMS products need to continue to evolve to add more functionality at smaller size and cost. The current SIP approaches cannot support this roadmap.