The Importance of Modeling Thermal Package Stresses in MEMS Devices

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Overview

- Introduction to MEMS
- MEMS Packaging Requirements
- Modeling Stress in MEMS Devices
Fairchild MEMS Milestones

- **1960s**
  - Developed strain gauge based pressure sensor for US Army C5 airplane
  - Started development of piezoresistive pressure sensors based on technology originated at Bell Labs
    - Art Zias, Gene Burk, Don Lynam
- **1972** - First Silicon Valley MEMS startups:
  - IC Transducers
  - National Semiconductor
- **1986** - Provided wafer fab equipment to NovaSensor
  - Schlumberger owned Fairchild and was NovaSensor’s investor
- **1999** - Licensed MEMS process Summit V from Sandia
  - Started production of MEMS devices for optical networking
  - Closed line in 2004 after optical networking bubble burst
- **2010** - Acquired Jyve to enter consumer market
Introduction to MEMS

- **MEMS**: Micro Electro Mechanical Systems, or...
  - Diversified family of non-electronic ICs (mechanical, optical, fluidic, etc.)

- Silicon is almost a perfect mechanical material for sensors:
  - No mechanical hysteresis
  - Comparable strength to steel
  - 3X lower density
  - Batch fabricatable

- Key challenges:
  - Lack of standardization
    - One device – one process – one package – one test system
  - Difficult process integration
MEMS Lifecycle Landscape

Yole 2011
TPMS (Tire Pressure Monitoring System)

- Mandated by multiple countries
  - US, Europe, China
- Market: 400 million units in 2015
  - Current ASPs:
    - $2.75 for the IC
    - $5.50 for the module
- Needs to operate in a tire
  - High humidity
  - Hot and cold
  - High linear and rotational velocity

Source: LV Sensors
Mobile MEMS

- BAW filters
- BAW duplexers
- RF switch / variable capacitor
- TCXO oscillators

- Accelerometer
- Gyroscope
- Electronic compass
- Pressure sensor

- CMOS Image Sensor
- Auto-Focus actuator
- Front camera
- ALS & Proximity sensor
- Microdisplay

Yole 2010
Next Generation Thermal Management

- MEMS etching technology enables on chip fluid cooling for microprocessors using microchannels etched into Silicon.

Cooligy/Emerson Network Power
Unit Market Forecast

- 15.8 billion MEMS devices in 2016 with a 24% CAGR over 2010-2016
MEMS will be a $19.5B market in 2016 ($8.6B in 2010) with 14% CAGR over 2010-2016
Diversified Packaging Needs

• MEMS based products (and their packaging requirements) are dramatically diversified:
  • By class of devices:
    • Mechanical devices (accelerometers, gyroscopes, pressure sensors, microphones, resonators, valves, etc.)
    • Optical devices (mirrors, spectrometers, gas chromatographs, displays, etc.)
    • Fluidic devices (reactors, pumps, filters, separators, etc.)
    • Bio/Nano devices (sensors, actuators)
  • By industry: same MEMS die may require different packaging for different markets:
    • Military
    • Avionics
    • Process control
    • Automotive
    • Medical
    • Consumer

• Different applications require MEMS devices to be exposed to different thermal environments
Samples of MEMS Packaging

Military sensors. Kulite

Disposable blood pressure sensor, NovaSensor

MAP sensor, Ford

TPMS, LV Sensors and Beru

Smart bandage with oxygen generator, IMEC

Process control pressure sensor, Rosemount
Packaging Challenges for MEMS

- Just like IC packages, MEMS packages must be optimized for reliability, signal integrity, form factor, and thermal dissipation, but that’s where the similarities end.

- Performance degradation is primary MEMS packaging concern:
  - Many devices sense stress or displacement, often with Å resolution, which is easily degraded by package induced stress (e.g., overmolding or material TC mismatch).
  - Temperature changes and thermal gradients in package create thermomechanical stresses and deformation in moving devices:
    - Electrostatic gaps can change uncontrollably.

- MEMS devices often require a specialized interface with the outside world:
  - Many devices interface directly with physical world:
    - Die must be exposed to high/low temperature fluid media (e.g., pressure sensor, fluidic devices, etc.).

- Some MEMS operate at high temperatures (e.g., 1000°C for in-cylinder pressure sensor).
Modeling Thermal Stress Impact on MEMS Performance
MEMS Thermal Stress Modeling

- Overmolded MEMS on LGA
MEMS Thermal Stress Modeling

- Package stresses come from CTE mismatch between all materials in the package

```plaintext
Plastic overmold (10ppm/°C)
MEMS (3ppm/°C)
LGA substrate (~14ppm/°C)
PCB (14ppm/°C)
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Package Deformation with Temperature Change

- Red = positive Z deformation

- When the temperature rises, the higher CTE materials at the bottom of the stack will expand more than the Silicon & plastic
  - This creates a “smiley face” bowing of the whole structure
Capacitive Sensors

- Parallel plate capacitors
  - Sense out of plane motion (i.e. Z axis motion)

- Sense comb capacitors
  - Sense in plane motion (i.e. X & Y axis motion)
Impact of Package Deformation on Mirror

- Parallel plate capacitors sense changes in capacitance between the moving mass and a stationary electrode.
- When the temperature changes, MEMS components will bend, and capacitance gaps will change.
- Changes in capacitance gap translate to changes in sensed metrics (e.g. mirror angle).
Impact of Package Deformation on Mirror

- If the mirror is offset to one side of the MEMS device, thermal stresses could induce bias problems.

- Mismatches between symmetric sense components create errors that are difficult to detect in operation.

- Die placement, mold compound variations, and other assembly effects can play a big role.
Optical Switching

- Switching optical networking signals can be accomplished with MEMS mirrors
- Fiber block can use MEMS fiber guides to align fibers to microlenses

- Optical devices require precision
  - Package stresses will be problematic
  - Heating of mirror flexures cannot be tolerated
    - Some of the optical energy will be absorbed by mirrors and must be properly dissipated
IMU (Inertial Measurement Unit)

• An IMU is a combination of an XYZ accelerometer and an XYZ gyroscope (6DOF)
  • Widely used to define position in defense, avionics, first response, robotic, industrial, and GPS assist applications

• Gyro measures angular rate and accelerometer measures acceleration
  • Accuracy degrades with time
    • From integration of signals into heading and position
  • Accuracy degrades by 10m in:
    • 1 hour for best sensors ($100,000)
    • 1 minute for medium cost sensors ($1,000)
    • 1 second for low cost sensors (<$10)

• The addition of an XYZ magnetic sensor, pressure sensor (10DOF), and pedometric algorithm reduces time dependence
  • Forecast to enter mobile market in 2013

Adapted from Yole 2010
IMU Integration with GPS Chip

- For improved integration with GPS, IMU can be packaged directly with GPS chip
- GPS chip radios generate power, temperature gradients
- MEMS performance will be impacted if interaction is not carefully designed
IMU Integration with GPS

• Temperature gradients will arise if GPS chip is doing a lot of work
  • Other active components will impact MEMS chip as well
  • If MEMS is placed at the center of active GPS chip
    • ~2°C overall chip temperature rise
    • 0.8 °C gradient across MEMS chip
Summary

• At the package level, thermal management in MEMS and ICs is very similar
  • Reliability, thermal dissipation, signal integrity, and small size/form factor are chief package requirements

• Two main differences
  1. MEMS devices must interact with the outside world
     • Packaging must allow interfacial MEMS components access to the outside world while protecting everything else from the outside world, sometimes limiting available packaging options
     • Some MEMS devices will absorb energy from the signals they sense, creating additional heat to be dissipated
  2. Many MEMS are inherently Electro-Mechanical components and the mechanical impact of thermal stresses will have a direct impact on MEMS performance
     • MEMS design can and must be optimized to tolerate thermal loads
     • Package level thermal loads and gradients must be studied and their impacts on MEMS performance minimized
     • FEA modeling is crucial
       • A good understanding of the MEMS operation, temperature sources, AND package factors is crucial to successful thermal management of MEMS
       • Requires good partnership between MEMS designers and package designers

• Minimizing the impact of thermal loads on MEMS performance can only be achieved through synergistic package and MEMS design