Testable Design and Testing of Microsystems

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Abstract:

The market of microsystems, incorporating microelectronics with e.g. MEMS-based sensors and actuators increases rapidly. The often non-electrical sensors and actuators are notoriously difficult and/or expensive to test. As the entire micro system has to meet certain quality criteria for specific applications, new techniques are being developed.

This tutorial will show current test practices of several basic categories of microsystems, and also methods to reduce or circumvent test problems. In these approaches, good knowledge on defects in the systems is required, and design modifications or extensions are shown to ease the testing process.

Biography:

Hans G. Kerkhoff received his M.Sc. degree in Telecommunication with honours at the Technical University of Delft in 1977 and the Delft Hogeschool Award for his M.Sc. thesis. In the same year he became staff member of the chair IC-Technology & Electronics at the Faculty of Electrical Engineering, University of Twente in Enschede. He obtained a Ph.D. in Technical Science (micro-electronics) at the University of Twente in 1984. In the same year he was appointed associate professor in Testable Design and Testing at the Faculty of Electrical Engineering at the University of Twente. He advised 15 Ph.D. students in this research area and has (co-) authored over 200 publications.

In 1991, he became head of the research group "Testable Design and Test of Microsystems" of the MESA+ Research Institute and headed the MESA Test Centre (MTC). In 1992 he spent his sabbatical year at the test company Advantest in San Jose (CA), USA. From 1995 up to 1999, he worked in addition part-time at the Philips Research Laboratories in the VLSI Design and Test Group at Eindhoven.

Testable Design for MEMS Sensors

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- MEMS in microsystems applications
- The MEMS market, and the cost of testing

● Testing MEMS

- Functional and structural approaches & examples
- Domain-specific handlers and ATE

● DfT for MEMS

- Domain input and output interfaces & examples

● BIST in MEMS

- Several approaches & examples

● Conclusions

MEMS: Many Applications

● **Transport**

- Safety-critical car microsystems (e.g. airbag)

● **Industrial & environmental**

- Control systems (e.g. pressure, flow)
- Seismic, pH, images etc.

● **Consumer**

- Telecommunication systems (e.g. microphones)
- Entertainment (CD/DVD players/recorders)
- Computer peripherals (e.g. discs, inkjet printers)

● **Healthcare**

- Microfluidic systems (e.g. drug synthesis)

Test Degree Application Dependent

⁴

- Consumer products
- Environmental
- Industrial products
- Transport (safety-critical)
- Health,

Higher test budget

Some established

airbag

accelerator

Optical mirror

Flow sensing

Inkjet printer

Others promising & emerging

(courtesy INTEL)

High-Q Oscillator Testing

(courtesy DIMES)

Oscillator testing is difficult
Measuring osc. properties

Testable Design for MEMS Sensors

Promising: MOEMS for Interconnect⁸

(courtesy IBM Zurich Research Labs)

Testable Design for MEMS Sensors

The MEMS Market (1)

10% of Microelectronics Market
19% increase annually

(Source: Yole Development)

The MEMS Market (2)

Conventional

- Inertial (Accelerometers)
- Pressure & flow

Emerging

- RF MEMS
- Optical MEMS (MOEMS)

Optical MEMS 2003-2008 Market (Yole source)

- Market will grow from \$ 756 million in 2003 to \$ 3089 million in 2008

Cost Division in MEMS

- Testing and related packaging can reach 70% of total costs

Division in costs in pressure MEMS

- Studies show that doing electrical wafer tests pays off due to expensive packaging

MEMS Processing

- **Substrate**
 - Silicon
 - Other (e.g. glass)
 - **Bulk micromaching**
 - Substrate is **part** of the MEMS operation
 - **Surface micromaching**
 - Substrate is **carrier** of the MEMS structure
-
- **Different technologies, complete different defects**
 - besides electrical also other (e.g. mechanical) issues

Very Many Different Defects ...

- pinholes, tox change

- high-R vias ,
- V_g variation

fluidics

thermal bonding

RF stress & stiction

MEMS Microsystem Testing Issues

- **Lack of defect origins & faultmodels because specific, (relative unmatured) processes**
 - stiction, cracks, voids, etc. (surface, bulk micromachining, LIGA)
- **Multi-domain design, fault simulation & test**
 - VHDL-AMS, domain interface circuits
- **Heavily influenced by packaging & environment**
 - stress, crosstalk & temperature, humidity, pressure
- **No standards & no knowledge spread by companies**
 - different customized packages, proprietary solutions

MEMS, Test and Packaging

- Microelectronics: protect chip from outside influences
- MEMS sensors / actuators: interact with outside
- MEMS functional operation critical to package design
- Device calibration and test closely linked to package
- MEMS packaging often more expensive than device
- Difficult to test, except electrical, prior to packaging

Packaging Interaction Modelling

(Courtesy QinetiQ, NoE PATENT)

Stress / humidity
pressure PCM

Develop for a particular
package, stress etc. tested
simulated behaviour

MEMS
model

Package
model

Interaction
simulation

Real
MEMS
behaviour

MEMS Design, Modelling & Simulation

(Courtesy Coventor, MEMSCAP)

(Courtesy C3M, NoE PATENT)

Testable Design for MEMS Sensors

Specification-Based MEMS Testing

- Optical MEMS: e.g. an optical switch
- RF-MEMS: e.g. an RF switch
- Inertial MEMS: accelerators
- Flow & Pressure MEMS: e.g. microphone
- Fluidic MEMS: e.g. inkjet printer head + reliability

Generic Approach MEMS Testing

- **Electrical wafer tests: conventional ATE**
 - some started proprietary multi-domain wafer tests
- **Packaged full specification test: added special domain interfacing**
 - these are proprietary and not made public
- **Environmental tests: humidity, pressure, temperature**
 - several general solutions possible

BASIC PROBLEM: obtaining high throughput!
And hence low costs !

Optical MEMS: Optical Switch (1)

Basic operation & MEMS implementation

(Courtesy MESA+ IOMS)

Optical MEMS: Optical Switch (2)

Bulky test environment & functional parameter tests

Test set-up

Results

Optical MEMS: Optical Switch (3)

- Many **defects** invisible during specification tests
- laser diodes & opto diodes could be used for DfT/BIST

defects

Testing MOEMS: Optical Switch (4)

- Different specialized ATE available. Opto relatively easy to convert

(Courtesy Flextronics & Dynamix)

Testing MEMS-based RF Switches (1)

(Courtesy IMEC)

Defects: (stiction, stress)

Influence of Packaging

Testing MEMS-based RF Switches (2)

(Courtesy IMEC)

results

MEMS-based RF Switches

(Courtesy Philips)

Humidity & Pressure Test Setups

Simulation & interference test

Measurements in Nitrogen & ATE

Fixed humidity (Courtesy Philips)

(Courtesy Agilent)

(Courtesy
Rhode Schwartz & Suss)

Testable Design for MEMS Sensors

Multisite RF Antennas Testing

MEMS-based antenna & Schottky diode

Inertial MEMS: Accelerators, Gyros 1³⁰

Some accelerometers

Functional tests:
e.g. resonator f
and sensitivity &
offset calibration

Stimuli: g , frequency, environment: T and RH

Inertial MEMS: Accelerators, Gyros 2³¹

Wafer shaker chuck

defects

(Courtesy CMU)

Inertial MEMS: Production Test

Large established market:
> 100 million parts annually

Shakers

Gravity handlers: g, frequency, T

(Courtesy Motorola)

Specially developed
Multitemp handlers

Inertial MEMS: Structural Testing

Defect

Defect model

(Courtesy CMU)

Output from test

Do sensitivity analysis (A,f, etc) defect detection -> ATPG
Add DfT if required for enhanced fault coverage

MEMS-based Flow Microsystem (1)³⁴

(Courtesy MESA+ TST)

Characterization test set-up

Results

*MEMS-based Flow Microsystem (2)*³⁵

hair orientation

stress

MEMS Pressure Interface

Using a pressure chamber

(Courtesy Memunity)

loading, time
consuming !

Vacuum chamber

(Courtesy Corner Intellig.)

Testable Design for MEMS Sensors

MEMS Pressure Microsystem

Pressure
sensor

(Courtesy Suss / Microtec)

Results

Test set-ups

Inkjet Testing & Reliability

Nozzle: 60 μm
 Droplet: 50 μm
 Frequency: 8 kHz

(Courtesy Imtec)

Electrical test at wafer (e.g. heater), imaging later

Inkjet MEMS & Reliability

(Courtesy Imtec)

Reliability is big issue in MEMS (safety)

Testable Design for MEMS Sensors

Quality Metrics: Structural Test & DfT

- Quality needs a unit of measure (like e.g. FC)
- Functional / specification-based tests are not sufficient to detect the different defects
 - Like analogue electrical, domains feature masking etc.
- Should detect on the basis of expected defects
- DfT could be required to increase observability & controllability of local points of interest
- Often after front-end electronics (noise, amplitude)

Design for Test

- First step is bidirectional domain conversion, second step is signal choice & signal processing
- Complexity of on-chip bidirectional conversions is highly dependent of domain: basically sensor/actuator
- Relative simple conversions: e.g. temperature, magnetic field, optical
- More complex conversion: gas flow, fluidic flow & pressure

Example of DfT for Microsystem (1)

architecture of Compass Watch

Example of DfT for Microsystem (2)⁴³

Test path of Compass Watch

Example of DfT for Microsystem (3)

Check on multiplex & measure

Stimulation & Observation of MEMS

Cumbersome interfaces and often slow

Generic Design for Test Approach

Possible DfT Interfaces for MEMS

Domain	Stimulus device	Observe device	complexity
Temperature	Heater resistor	Temp resistor	++
Magnetic B	Coil	Coil / B sensor	+
Light	Photo diode	Photo transistor	- -
Pressure	Heat membrane	Piezo resistor	-
Movement	Comb structure	Capacitor /piezo	--
Fluidic flow	FlowFET	Heat / sense R/C	--

Some DfT Components for MEMS

heater & piezo R

(Courtesy TIMA)

stim & pickup coil

Actuation & sense comb

FlowFET, Flowsensor

Typical Fluidic Test Setup

- Injection
- Valves
- Slow

Testing Fluidic Flowsensor & Pump

Mechanics creates problems

- DfT interfaces: - capacitive, switch (metal layers)
- piezoresistive

Electrical DfT in MAS System

Basic scheme

(Courtesy Twente Micro Products & HP)

implementations

DfT MAS

Use electrical wafer pre-tests
before packaged fluidic
functional tests

Architecture Analogue MEF Array

Interface electronics

module-based array

Testing Interface Electronics

Use Iddq monitoring

High-level Multi-domain Simulations

MathLab , VHDL-AMS are being used in multi-domain

particle jamming

leaking

addressing

System simulations reveal possible test approach!
Like in analogue parameters, speed and magnitude

VHDL-AMS Fault Simulations (1)

VHDL-AMS Fault Simulations (2)

basic core & 4*4 array

VHDL-AMS Fault Simulations (3)

Testable Design for MEMS Sensors

MEMS Built-In Self-Testing (BIST)

- **Generate actuation stimuli locally**
 - Heating resistors
 - Electrostatic force
 - Magnetic
 - Piezoresistive resistors

+ control electronics
+ signal processing
- **Sensing / observation locally** + comparison
 - Capacitive sensors
 - Electrostatic force
 - Magnetic
 - Piezoresistive resistors

Some MEMS BIST Approaches

- On-line testing via direct / indirect mixing of the test-signal with original signal
 - e.g. via modulation or DC superposition (e.g. Azais, Richardson, ETS05)
- Off-line testing via oscillation method
 - feedback of output to input, via network (Nouet, VTS02)
- Off-line testing via MLS application and subsequent on-chip HW correlation
 - IR sensor array (Mir, ETS05)
- Differential V/g actuation & measurement evaluation
 - accelerometer

Possible BIST Approach

- Magnetic stimuli relative easy made
- Check coil (e.g. R)
- Check fluxgates

Possible BIST Approach: IR Imager

- Uses heat absorption and Seebeck effect
- Choose cell by x,y, and via test, V_{test} the heater is activated
- Output is available via thermopile +,-
- Signal processing is off-chip and pure functional
- A transient input signal is being used

Self-Test Principle IR Imager

Digital (Droplet) Microfluidics

insulator
substrate

transport, merge, split & mix possible

Transport droplets via surface tension control. Resembles CCD clocking mechanisms.

(Courtesy Duke Uni.)

Testing Digital (Droplet) Microfluidics

inject, detect & concurrent testing

also BIST
and reconfig.

(Courtesy Duke University)

Isolation
degraded
electrode

Anchor, Beam and Finger Defects

Several defects cannot be detected by specification - based tests such as resonant frequency and sensitivity

(Courtesy CMU)

Selftesting Accelerometer

Two actuations are used and two nodes are compared.
This results in wafer defect detection capability

(Courtesy CMU)

Selftest Accelerometer using M-field

(Courtesy ESAT)

Uses permanent magnet and suspended beam **Al coil**.
Provides more (elec.st.) realistic movements (14 g)

Conclusions

- Testing of MEMS-based microsystems is one of the potential **show stoppers** for mass production
- Specification-based testing done predominately, defect-based hardly just like in analogue microelectronics
- Large local effort in MEMS handlers
- Relatively little knowledge on defects or how to detect them. System simulation required for quality!
- Very little DfT or BIST on-board currently. Expected to come soon. **Structural test is way to go.**

Questions