Process Technology to Fabricate High Performance MEMS on Top of Advanced LSI

Shuji Tanaka
Tohoku University, Sendai, Japan
More than Moore: Diversification

Integrated inertia sensors

Integrated health care devices

Implantable devices

High performance integrated sensors

Self-controlled one-chip sensors

One-chip multiband/ tunable wireless chips

Present

~2015

~2020

~2025

Smaller

More intelligent

More distributed
Multiband Wireless Communication

- **GSM/PDC**
  - 800 MHz
  - 900 MHz
  - 1.9 GHz

- **W-CDMA**
  - 1.92 ~ 1.98 GHz UL
  - 2.11 ~ 2.17 GHz DL

- **PHS**
  - 1.88 ~ 1.92 GHz

- **W-LAN**
  - 5.16 ~ 5.35 GHz
  - 2.4 ~ 2.48 GHz

- **Digital TV**
  - 470 ~ 770 MHz

- **WiMAX**
  - 2.5 ~ 2.7 GHz

- **4th Gen.**
  - 800 MHz
  - 900 MHz
  - 1.9 GHz

Multi-band wireless communication chip for W-CDMA + GSM/GPRS/EDGE (Qualcomm, QSC6240)
Real one-chip solution enables not only advanced mobile communication systems but also ubiquitous network sensors, wireless healthcare chips etc.

Integration of advanced LSI and “mechanical” devices (SAW/BAW filters, clock oscillators, RF MEMS switches, variable capacitors) is a key.
A tiny capacitance change (12 zF) corresponding to $1.6 \times 10^{-4}$ Å displacement is detectable by the embedded integrated circuit in the gyro.
Integrated Accelerometer (Analog Devices)

On-CMOS structure

Poly-Si sensor structure on 3 µm-ruled, W-metalized BiCMOS
Poly-Si annealing at 1100 °C for 30 min, Impossible to fabricate in LSI foundry

SOI MEMS structure

Single crystal Si sensor structure beside 0.6 µm-ruled, Al-metalized CMOS
Compatible with advanced LSI from LSI foundry, Low space efficiency

Judy et al., Hilton Head Island WS 2004, 27
Digital Micromirror Device (TI)

Hornbeck, IEDM 2007, 17-24

- 10~16 μm square micromirrors
- ~2 μs response time
- 8.5 V driving voltage
- ±12° tilt angle
- $848 \times 600 = 508800$ pixels for SVGA
  - $\sim 1280 \times 1024 = 1310720$ pixels for SXGA
Applications of DMD

- Rear-projection television
  - Panasonic

- Mobile projector
  - NEC
  - Weight: 1 kg

- Projector for cinema complex
  - NEC
Metal Surface Micromachining for DMD (TI)

1. Sacrificial resist layer
2. Al and SiO₂ mask for hinges
3. Al and SiO₂ mask for beams
4. Al etching for beams and hinges
5. Sacrificial resist layer and Al mirror
6. Sacrificial resist etching


Hornbeck, IEDM 2007, 17-24
MEMS-LSI Integration using Ge Sacrificial Layer

- Multi-freq. AlN Lamb wave resonator monolithically integrated with LSI
- Application to one-chip high-speed communication devices

Collaboration with NDK

1. Ge patterning and SiO₂ deposition

2. Metal patterning and AlN deposition

3. AlN and Au/Cr patterning

4. Ge sacrificial etching

310 MHz

100 μm
Electrostatic-Actuated Capacitive Shunt Switch

On state

Dielectric layer (SiO₂) Ni bridge

Off state

Notches for close contact

Sacrificial PR (3.5 µm) Sacrificial PR (1.5 µm)

GND Signal GND

Driving voltage: 38 V

Insertion loss

Isolation

Frequency (GHz)

Insertion loss (dB)

Isolation (dB)

Yuki et al., Sensor Symposium 2007
Wafer-Level Packaging of RF MEMS Switch

1. Molding dry film resist
2. Exposing dry film resist
3. Laminating molded dry film resist and exposing
4. Developing and over-coating

RF MEMS switch packaged by dry film resist

Yuki et al., Sensor Symposium 2007
Phase Shifter Using RF MEMS Switches

- **Switching line type**

- **Reflection type**

  Reflection-type phase shifter using RF MEMS switch (Taiko Denki & Tohoku Univ.)
Memory Effect of Metal Hinges in DMD

A. B. Southeimer, IEEE 40th Annual International Reliability Physics Symposium, Dallas, TX, 2002
Wafer Bonding-based MEMS-LSI Integration

1. Preparation of a device layer on a support wafer
   - Support wafer
   - Interlayer: e.g.) SiO₂, Polymer
     - Device layer: e.g.) Single crystal Si, Piezoelectric materials, Diamond, Compound semiconductors
   - Adhesion layer

2. Fabrication of a LSI wafer
   - LSI wafer
   - E.g.) SiO₂, Polymer

3. Low temperature bonding of the device layer and the LSI wafer

4. Removal of the support wafer/Thinning of the device wafer
   - LSI wafer

5. Fabrication of MEMS (e.g.) RF MEMS switch, variable capacitor) or SAW/BAW devices
   - Electrical connection

6. Release of the device by sacrificial etching
Single Crystal RF MEMS Switch on Top of LSI

- Metal anchor
- Actuation electrode
- Single crystal Si cantilever
- Signal line

RF MEMS switches on a dummy LSI wafer

- Metal anchor
- Single crystal Si cantilever
- Single crystal Si bridge

Graph:
- Y-axis: Height (μm)
- X-axis: Lateral length (μm)
- OFF (V_{drive} = 0 V)
- ON (V_{drive} = 8 V)

200 μm
Single-Crystal-Si-on-LSI (SOL) Technology

1. Fabrication of metal pads on a (dummy) LSI wafer

2. Bonding a SOI wafer on the LSI wafer using polymer interlayer

3. Etching of the handle and BOX layers

4. Patterning of metal electrodes

5. Shape formation of the device by reactive ion etching

6. Cu electroplating using photoresist molds for electrical connection

7. Removal of the photoresist molds

8. Sacrificial polymer etching by O₂ ashing to release the device

LSI wafer
SOI wafer
Polymer
Cu electroplating
Photoresist mold

200 μm
1. Electrically-coupled AlN/Si composite thickness-mode filter

2. Mechanical-coupled AlN/Si composite disk array filter

Collaboration with Mr. Matsumura (NiCT)
Single-Crystal-Si-on-LSI (SOL) Technology

1. Wafer bonding using polymer

2. Handle layer and BOX layer etching

3. Metal patterning

4. AlN deposition and patterning

5. Metal patterning

6. Si etching

7. Sacrificial polymer etching
Unpublished data
Share Wafer System in Tohoku University

Shuttle service

Given process → Call for devices
Registration from A corp., B univ. …

Share wafer system

Group A
Sensor circuit

Group B
Driver circuit

Group C
Oscillator circuit

Group D
Actuator circuit

Is there a common process?
Coordination with LSI foundry

Multiple devices in each shot

MEMS fabrication by each group

Delivery after chip separation

Full wafers to each group

Project members (NDA is concluded.)
Summary

• There is strong demands for monolithic integration of advanced LSI and “mechanical” devices such as clock oscillators, mechanical filters, switches and sensors. “More than Moore” with “Moore Moore” and “Biyond CMOS”

• There are varieties of existing MEMS-LSI integration technology, but they are not suitable for the above applications.

• We have developed new versatile microprocess technology for the monolithic integration of high-performance MEMS on top of advanced LSI.

• Using the developed technology, we fabricated RF MEMS switches/variable capacitors, RF mechanical resonators and filters etc.

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