1. Introduction

2. Integrated MEMS by adhesive wafer bonding
   - Principle and filters
   - Piezoelectric switches
   - Tactile sensor network
   - Massive parallel EB exposure system

3. Wafer level packaging

4. Open collaboration

5. Conclusions
Structure + sensor + circuit + actuator

Advantages

- **Miniaturization**
  (high sensitivity, low power, good spatial resolution, etc.)

- **Integration**
  (low cost, array etc.)

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**Trends of MEMS (Micro Electro Mechanical Systems) products (+13% in sales)**

- **1990**
  - Engine control
  - Blood pressure sensing
  - Accelerometer for airbag

- **2000**
  - Tire pressure monitoring
  - Gyro for camera
  - Oscillator
  - Print head

- **2010**
  - Microphone
  - MEMS switch
  - IR imager (Night vision)
  - Display (DMD)
Inertia sensors (SIP) MEMS chip + LSI chip

Array MEMS for display
(SOC) MEMS on LSI

MEMS for wireless communication
(Adhesive bonding of MEMS wafer on LSI wafer)
Hetero integration by adhesive bonding

MEMS on carrier wafer (Piezoelectric thin film etc.)

LSI wafer

After adhesive bonding and removal of carrier wafer

Piezoelectric filter

SAW filter on LSI

Tunable filter

LTCC wafer with through-via interconnection

Piezoelectric MEMS switch etc

Piezoelectric MEMS switch on LSI

Dicing

Packaged hetero integration chip

Wafer level sealing

Hetero integration by adhesive bonding
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5. Conclusions
1) Film transfer using polymer → Device fabrication → Polymer removal

High temp. deposition

IC etc.

2) Device fabrication → Device transfer using polymer → Polymer removal

High temp. process

IC etc.

3) Film preparation → Device fabrication → Device transfer by bonding and polymer removal

Bonding & polishing

IC etc.
**Application of adhesive bonding**

**Tactile sensor**
Bonding with BCB (Cyclotene)

**Micromechanical resonator**
Bonding with polyimide
Partly etching of polymer after bonding

**SAW filter on LSI**
Bonding with UV curable resin
Remove after temporary bonding

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Sacrificial layer

Surface micromachining

Polymer

Adhesive bonding
Removal of polymers by ozone in acetic acid

(H.Yanagida, IEEE MEMS2011, 324)
AlN/Si composite disk resonators and FBAR for multiband wireless systems
FBAR (Film Balk Acoustic Resonator)

CMOS-FBAR voltage controlled oscillator

1. Bonding of LiNbO₃ to Si
   UV curable resin  LiNbO₃
   Si (carrier wafer)

2. Lapping and polishing of LiNbO₃

3. Al electrode patterning and trenching
   Al

4. Au bump formation
   Au
   Si (LSI)

5. Au-Au bonding

6. Device release by ashing resin
   SAW device

(K.-D. Park, M. Esashi, S. Tanaka, IEEJ The 26th Sensor Symposium, 37 (2009))
SAW oscillator on LSI (502 MHz)
Tunable filter on breadboard using Si variable capacitors and SAW filters

(M. Kadota et al. (Murata Mfg.), Jpn. J. Appl. Phys., 49 (2010) 07HD26-1)

Monolithic tunable filter using MEMS variable capacitors and SAW filters

(T.Yasue, T.Komatsu et.al., Transducers 2011)
Tunable SAW filter using MEMS variable capacitor

(T. Yasue, Transducers 2011, Beijing (2011) 1488)
1) Patterning of Au/Cr electrodes

2) Fabrication of SAW resonators
   IDT

3) Fabrication of stop bumps
   Bump

4) Patterning of PR sacrificial multilayer
   PR

5) Cu seed deposition
   Cu

6) Patterning of PR mold
   PR

7) Ni electroplating
   Ni

8) Photoresist removal

9) Cu wet etching

10) O$_2$ ashing for release

Fabrication process of tunable SAW filter using MEMS variable capacitor

(T. Yasue, Transducers 2011, Beijing (2011) 1488)
BST (\(\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3\)) varactor

Transferred BST varactor
(Tuning ratio of 1.6 at 3 V)

Small size ferroelectric variable capacitor for tunable SAW filter
Laser debonding

Selective transfer by laser debonding

PZT MEMS Switch on LSI

(Matsuo, Moriyama, Esashi, Tanaka (Tohoku Univ.), IEEE MEMS 2012, 1153-1156)
Fabrication process of PZT MEMS Switch on LSI

(Matsuo, Moriyama, Esashi, Tanaka, IEEE MEMS 2012, 1153-1156)
CMOS switch control circuit

VDD : power supply, 3.3V
CLK : clock signal, 3.3 V, 5 MHz
IN_1, IN_2 : switching signal, 3.3 V
DOUT_1~4 : D flip-flop’s output
Common 2 wires tactile sensor array (polling type)

(1,000 Tr./chip in our lab., 1,000,000 Tr./chip in company, 10,000,000,000 Tr/chip now)
Tactile sensor network for robot (event driven type)
(M.Makihata, M.Muroyama, 26th Sensor Symposium (Oct. 15-16, 2009))
Fabrication process of tactile sensor

(M. Makihata, M. Muoyama et. al., 2012 MRS Spring Meeting, San Francisco (2012) B3.2)
Tactile sensor network

(M.Makihata, M.Muroyama et.al., 2012 MRS Spring Meeting, San Francisco (2012) B3.2)
nc (nanocrystalline)-Si emitter array fabricated on SOI substrate

(N.Ikegami et.al., Active-Matrix nc-Si Electron Emitter Array for Massively Parallel Direct-Write Electron-Beam System, SPIE 2012 Advanced Lithography (2012/2/12-16) San Jose, USA)
Massively Parallel EB (Electron-Beam) Exposure System
Electron source process
1. Introduction

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5. Conclusions
MEMS have moving parts

→ Direct molding with plastics can not be done.

→ **small size** (chip size encapsulation, suitable for surface mounting)

→ **high yield** (protection of MEMS structures during dicing)

→ **high reliability** (hermetic sealing)

→ **low cost** (minimal investment for assembly, no use of expensive ceramic packages etc)

**Wafer level packaging**
1. Green sheet
2. Punching
3. Plugging holes with Au paste
4. Laminating
5. Sintering
6. Anodic bonding

LTCC with through-via interconnection

1. Production of LTCC wafer
2. Wet etching of LTCC wafer
3. Wafer alignment
4. Anodic bonding

(a) Porous Au bump by etching of LTCC
(b) Nano-porous gold bump by etching out of Sn from Au-Sn (Collaboration with FhG ENAS)
(c) TLP (SLID) bonding using Cu-Sn-Cu

Electrical Interconnection from the feedthrough of LTCC
Metal-metal bonder
1. Introduction

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5. Conclusions
MEMS process facility for 20 mm wafer

Many process equipments have been made in house.

Simple and basic equipments are suitable for training people who have experiences of all the process and for developing new devices taking advantages of process flexibility.

The facility has been shared by many laboratories. More than 100 companies dispatched researchers (full time, 2 years).
Ricoh, Toyota motor, Pioneer, Nippon signal, Toppan TDC, Kitagawa iron works, Sumitomo precision, NIDEC COPAL elec. Nikko, Toyota central R&D lab, Nippon dempa kogyo, Japan aviation elect. Ind., MEMS core, MEMSAS, Furukawa Electric, Denso Laboratories in Tohoku Univ.

Shared CMOS LSI wafer
Next generation wireless system group

Yugami, Tanaka, Yamaguchi, Endo, Iguchi  Toppan TDC, Nippon Dempa Kogyo

Multi-frequency Lamb wave oscillator

310 MHz

100 µm

Sensor network, functional sensor group

Kuwano, Miura, Ono, Tanaka, Nagasawa, Muroyama Kitagawa, Sumitomo precision product, Nidec copal electronics, Toyota, Toyota Central R&D, Pioneer

Tactile sensor network

Optical microsystem group

Hane, Kanamori, Kawai
Ricoh, Nippon signal, Toyota, Toyota Central R&D, Furukawa Electric

2D PZT optical scanner

Biomedical microsystem group

Matsue, Nishizawa, Haga, Kusu
Japan aviation electronics industry
MEMSAS

Bio LSI

Fabrication test equipment group

Samukawa, Esashi, Miura, Ono, Yamaguchi, Kumano, Miyashita
MEMS core, Nikko

Metal-metal boner

Technology society system working group

Harayama, Sionoya, Kawai, Miyashita, Matsuzaki

Shared patent

Innovation center for fusion of advanced technologies 2007~2016FY
Tohoku Univ. Aobayama campus

Jun-ichi Nishizawa Memorial Research Center

Micro/nanomachining research and education center (2 inch LSI process line)

Micro/nanomachining Research and Education Center (MNC)

Tohoku Univ. Aobayama campus

Jun-ichi Nishizawa memorial research center (4/6 inch MEMS process line) (Hands-on access fab.)

MEMS prototyping room in Tohoku Univ.(20mm) (Initial stage prototyping)

AIST MEMS building in Tsukuba (8 inch process line) (R.Maeda) (Production stage prototyping)

Prototyping facilities World-leading innovative R&D project 2010 ~ 2013FY
Companies which cannot prepare their own facility dispatch their employees to operate equipments by themselves.

Shared facility for industry to prototype MEMS devices (4 / 6 inch)

**Hands-on access fab.** (Nishizawa memorial research center in Tohoku Univ.)

Contact person: Assoc. Prof. Kentaro Totsu  totsu@mems.mech.tohoku.ac.jp
MEMS Core Co.Ltd (President : K.Honma)
MEMS contract development, prototyping and small volume production (2001~)

http://www.mems-core.com/
MEMS switch factory
(Advantest components (Sendai))

MEMS switch for LSI tester

Advantest components
(Qty. 1000)

MEMS switch for LSI tester

Immune to electrostatic discharge up to 1000V
Wide frequency range (DC~10GHz)
Advantest’s high-frequency MEMS relay utilizes piezoelectric actuation to achieve low power consumption and high reliability. Via Advantest’s proprietary deposition technology, the relay features a piezoelectric film only 1 micron thick, making low actuation voltage possible. The relay also has high reliability, using contact-point control technology honed in Advantest’s semiconductor testing equipment, and it can handle up to 20 GHz high-frequency transmission, using Advantest’s high-frequency measurement technology.

MEMS Relay Applications

Membrane Testing Equipment, High-Speed Communications Devices, High-Frequency Measurement Equipment

MEMS Relay Production Process

RF MEMS Switches
RF MEMS switches are mainly manufactured by these three steps:

1. 1st Step: Si Wafer Actuation Unit Production
   - Si wafer actuation unit (2nd layer) including bimorph cantilever

2. 2nd Step: Glass Wafer Gluing
   - Gluing of three stacked wafers, including 3rd layer glass wafers for casing

3. 3rd Step: Cutting
   - MEMS switch cut from three layer wafer
MEMS Training Program in Sendai MEMS park consortium

Since Apr. 2007. Fee 1 million yen. **Trainee participate with own subject.**

16 companies participated.

**Lectures on Internet School of Tohoku University**

**Planning, design**: 10 ~ 20 d

**Fabrication (4 inch process)**: 30 ~ 60 d

**Testing**: ~ 10 d

**Presentation, report**: 3 d

**Ex. Capacitive 3-axis accelerometer**

**Design**

**Training of Fabrication**
Nishizawa memorial research center

Shared facility for industry to prototype MEMS devices (4 / 6 inch)  Hands-on access fab.
Users approximately 80 companies
Sendai MEMS showroom (2012/5/16 renewal opening)

http://www.mu-sic.tohoku.ac.jp/showroom_e/index.html
A1 Electrical measurement: Galvanometer etc.
A2 Wired communication: Microphone, Headphone
A3 Wireless communication: Vacuum tube radio, Transistor radio
B1 Recording: phonograph (Edison), Vacuum tube magnetic tape recorder
B2 Computer: Mechanical computer, calculator
C1 Vacuum tube: Various vacuum tubes, Vacuum tubes for take-out, Manuals
C2 Transistor-IC: From vacuum tube to transistor, Development of LSI
C3 Haggerty’s forecast (1964)
D1 Optical equipments: Microscope x 3, Analog recording camera, 8mm movie etc.
D2 Optical instruments: Radiation thermometer etc.
E1 Hobby: Mechanical doll, Aibo, Micro flying robot and computer controlled model car
E2 Automobile museum: Model T Ford, Model A Ford
E3 Nishizawa memorial room
F Materials for take-out (history of technology)
H Books on the history of technology
I Materials related to Tohoku Univ. and companies

Historical Museum of Technology
http://www.mu-sic.tohoku.ac.jp/museum/
FhG Germany – Sendai city partnership signing ceremony in Munich (July 15, 2005)

FhG Germany – Sendai city partnership extension signing ceremony (July 13, 2010)

FhG Germany – Tohoku Univ. partnership signing ceremony in Sendai (Nov. 8, 2011)

Mayer of Sendai city Ms. E. Okuyama and president of FhG Prof. H.-J. Buringer

FhG Project center in WPI-AIMR, Tohoku Univ. (2012)
Signing ceremony (2012/6/11)

WPI-AIMR core members in IMEC (2012/6/21)
Pi’s Esashi, Ohno and Matsue

Strategic Partner
Tohoku U · Stanford U · EPFL

- One university from each region, Japan, USA and Europe
- Promotion of international research exchange
- Exchange of researchers and students

Hiroshi Kazui (Director, Tohoku Univ.) and Luc Van Den Hove (IMEC president)
Tohoku Univ. Micro System Integration Center

- MEMS prototyping facility (20mm □)
- Micro/Nanomachining research and education Center (MNC) (2 inch LSI)
- Hands on access fab. (4/6 inch)

MEMS Core (4/6 inch line)
- Annex Esashi lab.
- MEMS show room
- Sendai stealth dicing lab.

Hamamatsu Photonics. et.al.

Collaboration

MEMS PC member companies (80)

Local companies
- Advantest components et.al.
- Ricoh, Toyota motor, Pioneer, Nippon signal, Toppan technical design center, Kitagawa iron works, Sumitomo precision, NIDEC COPAL electronics, Nikko, Toyota central R&D labs, Nippon demma kogyo, Japan aviation electronics industry, MEMS core, MEMSAS, Furukawa Electric, Denso

R&D Center of Excellence for Integrated Microsystems (2007-2016) ~5MUS$ / Year

MEMS Park Consortium (MEMSPC)
- Sendai city

MEMS Industry Group in USA
- Germany FhG
- Italy Poly Tech. Torino
- Tokyo Univ. of Agriculture and Tech.
- Belgium IMEC
- USA U.C.Berkeley
- France LETI
- Chiba Univ.
- NICT
- Crestec
- Murata MFG

Funding program for world-leading Innovative R&D on Science and Technology (FIRST) (2010-2013) ~5MUS$ / Year

AIST Research Center for Ubiquitous MEMS and Micro (UMEMSME) (8 inch)

Nissan motors, Dainippon Printing et.al.

Tsukuba Innovation Arena (TIA)

France LETI
In the past

Company

University

Government research institutes

At present

Company

University

Government research institutes

In future

Company

University

Government research institutes

Application

Facility for prototyping

Basic
Efficient development for heterogeneous integration

Information from universities
(MEMS park consortium [http://www.memspc.jp](http://www.memspc.jp))

Free MEMS Seminar in Sendai (Aug. 22-24, 2007) 75 attendees
Free MEMS Seminar in Fukuoka (Aug. 20-22, 2008) 150 attendees
Free MEMS Seminar in Nagoya (Aug. 4-6, 2009) 100 attendees
Free MEMS Seminar in Tsukuba (Aug. 5-7, 2010) 211 attendees
Free MEMS Seminar in Kyoto (Aug. 9-11, 2011) 175 attendees

High-tech. small volume production

Efficient utilization of facilities

MEMS seminar
Conclusions

1. Adhesive bonding for Wafer-Level Hetero Integration
   (Filters, Piezoelectric switches, tactile sensor network, massive parallel EB exposure system).

2. Wafer level packaging using LTCC with through-via interconnection.

3. Open collaboration for MEMS on LSI.

Acknowledgment to collaborators

Assoc.Prof. S.Tanaka (RF MEMS)
Assis.Prof. M.Muroyama (LSI design)
Assis.Prof. S.Yoshida (Piezo electric)
Guest Prof. T.Gessner (Packaging) (MEMS materials)
Assis.Prof. Y.C.Lin

FhG ENAS Germany