Wafer-level Heteointegration Technology and its Applications

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Sendai, Japan
Lecture room 階段教室, where Lǔ Xùn’ studied, in Katahira Campus

**Novel 「藤野先生」**

This novel is based on Lǔ Xùn’s experience in School of Medicine, Tohoku University (former 仙台医学専門学校) in 1904 ~ 1906. 藤野 嚴九郎 教授 Prof. Fujino was Lǔ Xùn’s supervisor.

先生 in Japanese 老師 in Chinese

Lǔ Xùn’s notebook

藤野厳九郎像
MEMS Facilities in Aobayama Campus

- New campus
- Graduate School of Engineering
- Subway station (under construction)
- Micro/Nano-Machining Research and Education Center (MNC)
- Microsystem Integration Center
- S. Tanaka Laboratory Cleanroom
Hetero-Integration

Ferroelectric/Piezoelectric materials
e.g. LiNbO$_3$

MEM device

Functional material

Integrated circuit

Frequency control
Optical modulation
Parametric oscillation
Detection
Actuation

Processing
Amplification
Memory
Detection

Si
Tactile Sensation on Whole Robot Body

Tactile sensor network for home and medical robots enables:

- Contact detection for collision safety
- Body contact communication

I. Kumagai et al., IEEE/RSJ’12 (2012)
Tactile Sensor Network on Robot

- CPU
- Hub
- USB cable
- Relay node
- Tactile sensor array (256 chips)
- Conformal installation
- Sensors
- Variable mounting density on Robot body
MEMS-on-CMOS Integrated Tactile Sensor

M. Makihata et al., 2012 MRS Spring Meeting

Capacitive sensing electrode

BCB polymer

Thinned CMOS wafer

I/O pad

Through-silicon groove

2.4 × 2.4 × 0.3 mm²
Data from Integrated Tactile Sensor

M. Makihata, M. Muroyama, S. Tanaka et al., 2012 MRS Spring Meeting

- Bus signal [V]
  - Preamble
  - Start Bits
  - Sensor ID
  - DATA (32bits)
  - CRC (16bits)
  - Stop Bits

- Time [μs]
  - 0 10 20 30 40 50 60 70 80

- Press
  - 360μs 480μs 600μs

- Release
  - 43 signals

- Decoded data
  - Threshold value: 165

- Time [ms]
  - 0 20 40 60 80 100 120 140

Threshold & Adaptation operation
Integration for Multiband Wireless Front-End

- Integration of acoustic filters and timing resonators on RF-CMOS
- Integration of many front-end filters for multiband wireless systems
- Frequency tunability enabled by MEMS (e.g. variable capacitor)
Pull-in voltage

\[ V_{PI} \approx \frac{0.54}{l^2} \sqrt{\frac{Eh^3d_0^3}{\varepsilon_0}} \]

**Al cantilever:**

\( E = 70 \text{ GPa}, \ h = 1 \mu m, \ l = 100 \mu m, \ d_0 = 3 \mu m \)

\( \rightarrow V_{PI} = 25 \text{ V} \)

**Al/AlN/Al cantilever:**

\( E = 320 \text{ GPa}, \ d_{31} = 3.125 \text{ pC/N}, \ h = 0.1/0.8/0.1 \mu m, \ l = 100 \mu m, \ d_0 = 3 \mu m \)

\( \rightarrow V_{p} = 18.5 \text{ V} \)

**Cu/Pt/PZT/Pt cantilever:**

\( E = 70 \text{ GPa}, \ d_{31} = 90 \text{ pC/N} \)

\( \rightarrow V_{p} = 2.4 \text{ V} \)
PZT-Actuated MEMS Switch on CMOS

Matsuo, Moriyama, Esashi, Tanaka (Tohoku Univ.), IEEE MEMS 2012

Bias electrode

GND
RF I/O
GND

Au
Contact
Pt
PZT
C

Al pad
LSI

Deflection (μm)

Driving voltage (V)

0 2 4 6 8 10
0 1 2 3 4 5 6 7
Deflection (μm)

V_{dd} GND IN2 DOUT1-4
IN1 CLK G S G
PZT-Actuated MEMS Switch on CMOS

Matsuo, Moriyama, Esashi, Tanaka (Tohoku Univ.), IEEE MEMS 2012

A-1. Fabrication of PZT MEMS structure
- Pt drive electrode
- Signal line
- PZT

Si wafer

A-2. Polymer spin-coating
- Polymer

Si wafer

B-1. Fabrication of electrodes and pads on IC
- Au

IC wafer

B-2. Polymer spin-coating
- Polymer

IC wafer

C-1. Bonding (A-2 and B-2)
- IC wafer

C-2. Etching of Si wafer and TiO₂ (Transfer of MEMS structures)
- IC wafer

C-3. Polymer RIE
- Al

IC wafer

C-4. Sacrificial polymer etching
- PZT cantilever

IC wafer
Tunable BST Varactor on CMOS Power Amp

- Transferred BST varactor
- Au electroplated inductor
- BCB bonding polymer

Parameter: Admittance (S)
- Frequency (GHz)
- Bias 0 V
- Bias 8 V

0.18 μm CMOS power amplifier (Kyushu Univ.)
Electrochemical Biosensor Array

Multi-project wafer LSI chip

Electrode array Electrode

250 μm

Enzyme kinetics analysis Cell respiration activity

Sub$_{\text{red}}$ Sub$_{\text{OX}}$ CO$_2$ O$_2$

Electrochemical bio-activity sensing

Immunoassay for diagnostics Cell-based assay for environmental monitoring

Collaboration with Prof. Matsue, Tohoku University
Wafer-Bonding-Based Integration: Problems

Steven Nasiri and Martin Lim, InvenSense, Inc.

*Market share > 20 % for 3-axis gyros in mobiles (2011)*

![Diagram of MEMS gyroscope integration](image)
Combo Sensors

**Combo sensor:**
- 3-axis accelerometer
- 3-axis gyroscope
- 3-axis magnetometer (e-compass)

STMicroelectronics
LSM9DS0 (4 × 4 mm²)
5 dies
- Accelerometer
- Gyroscope
- Magnetometer
- 2 ASIC

Bosch
BMX055 (3 × 4.5 mm²)
5 dies
- Accelerometer
- Gyroscope
- Magnetometer
- 2 ASIC

InvenSense
MPU-9250 (3 × 3 mm²)
2 dies
- Integrated 6-axis inertia sensor
- Magnetometer

Photographs: Romain Fraux (System Plus Consulting)
Selective and Multiple Die Transfer

(1) Wafer bonding

MEMS
Glass support wafer
Polymer

180°C

(2) Laser irradiation

THG Nd:YVO₄ laser (λ = 355 nm)

(3) Selective die transfer

Reusable
Reusable
FBAR and Sustaining Amplifier IC

S. Taniguchi et al. (Taiyo Yuden), IEEE Ultrasonics Symposium 2007

Designed and fabricated by Asahi Kasei Microelectronics
Selective and Multiple Die Transfer

4 times of die transfer were demonstrated using the same MEMS wafer.

K. Hikichi … S. Tanaka, IEEJ Sensor Symposium 2013
Integrated/Packaged 2 GHz FBAR Oscillator

Phase Noise 10.00dB/Ref -20.00dBc/Hz

Carrier 1.9624 GHz

Offset (Hz)
LiNbO$_3$ on IC One-Chip SAW Oscillator


SAW resonator on 128° Y LN

Au bump

Integrated SAW oscillator

500 µm
Phase Noise of One-Chip SAW Oscillator

\[ \Delta f_n \sim \Delta f_{-3} \]

\[ \frac{f_0}{2Q} \approx 200 \text{ kHz} \]

\[ Q \approx 1250 \]

\[ Q \approx 1250 \]

Loop BW 3 kHz

-110
-120
-130
-140
-150
-160
-170

10 kHz
100 kHz
Frequency offset
502.5 MHz

10 kHz
1 MHz
3 MHz

RF Atten: 5 dB
Top: -100 dBC/Hz

Marker 1 [T1]
100 kHz
-147.36 dBC/Hz

502.5 MHz

10 kHz
100 kHz
3 MHz

SPR OFF
TH 0dB
TV White Space Cognitive Radio

Monthly average traffic of mobile communication in Japan

Digital TV band

Sendai

Ishinomaki

40 ch × BW 6 MHz = 240 MHz

Monthly average traffic (Gbps) × 2.2/year
Design of Tunable SAW Filter (Chiba Univ.)

M. Inaba, T. Ohmori, K. Hashimoto (Chiba Univ.), Jpn. J. Appl. Phys., 52 (2013) 07HD05

Y: SAW resonator
C: Varactor

10 SAW resonators and 10 varactors integrated on 42° Y LiTaO₃

Relationship between capacitance and bandwidth

<table>
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<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C'</th>
<th>C</th>
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<tbody>
<tr>
<td>(C_{p1})</td>
<td>Small</td>
<td></td>
<td>Large</td>
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<tr>
<td>(C_{p2})</td>
<td>Large</td>
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<tr>
<td>(C_{s1})</td>
<td>Small</td>
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<td>(C_{s2})</td>
<td>Large</td>
<td></td>
<td>Small</td>
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Simulation

Insertion loss (dB)

Frequency (GHz)
Hetero-Integration of BST Varactor

(Ba$_{1-x}$Sr$_x$)TiO$_3$

BST is deposited at 600°C or higher.

Sapphire wafer removal

42° Y LiTaO$_3$

LT sub.

IDT

BST varactor

LT sub. bonding

Sapphire wafer removal

LT sub.

BST varactor

Laser pre-irradiation

Normalized ε

3

5

7

Applied voltage

0

ε

tan δ

27

(BST Mfg.)

Al

Pt

Au

BST

Pt

Au

LT sub.

Au

BST

Laser

Sapphire sub.

pt-Au bonding

LT sub.

LT sub.
Transferred BST on LT SAW Wafer

4 mm × 4 mm
Bandpass Characteristic and Application

**Insertion loss (dB)**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>0.96</th>
<th>0.98</th>
<th>1.00</th>
<th>1.02</th>
<th>1.04</th>
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<tr>
<td>C&lt;sub&gt;S1&lt;/sub&gt;, C&lt;sub&gt;P1&lt;/sub&gt;: 0 V, C&lt;sub&gt;S2&lt;/sub&gt;, C&lt;sub&gt;P2&lt;/sub&gt;: 7 V</td>
<td></td>
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<tr>
<td>C&lt;sub&gt;S1&lt;/sub&gt;, C&lt;sub&gt;P1&lt;/sub&gt;: 7 V, C&lt;sub&gt;S2&lt;/sub&gt;, C&lt;sub&gt;P2&lt;/sub&gt;: 0 V</td>
<td></td>
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</tbody>
</table>

**TV white band cognitive WiFi system using tunable filter (NICT)**

- Tunable SAW filter inside Antenna port
- Tunable SAW filter
- DA converter
- Rx
- Tx

- Image of circuit board with labeled components.
Summary

1. Devices are always getting smaller and more functional, and wafer-level heterointegration technology is a powerful method beyond SiP (System in Package) approach.

2. A network tactile sensor for human-friendly robots was constructed by the wafer-level adhesive bonding of a capacitive force sensor and a LSI.

3. Functional thin films (PZT, diamond etc.), which are not compatible with CMOS, were transferred from Si wafers to LSI wafers, and integrated devices were prototyped.

4. A one-chip tunable filter for TV white space cognitive wireless LAN was made by the monolithic integration of SAW resonators and BST varactors. The BST thin film was transferred from a sapphire wafer to a LiTaO$_3$ wafer by laser-assisted debonding technology.
S. Tanaka Laboratory Members

Professor 6
Staff 6
PhD course student 9
Master course student 6
Undergraduate 7
Research student 2
Visiting researcher 3
In total 42
Collaborators 5+
(Microsystems Integration Center)
Please visit S. Tanaka Laboratory website at http://www.mems.mech.tohoku.ac.jp/index_e.html

Research and Development of Micro-Nanodevices for Healthcare, Safety, Energy Saving, Advanced Communication, Robot Control etc.

Our core competence is MEMS technology!

Students from other universities and foreign countries are welcome. Please join our laboratory regardless of your experience in MEMS field.

Message to students  Message to companies