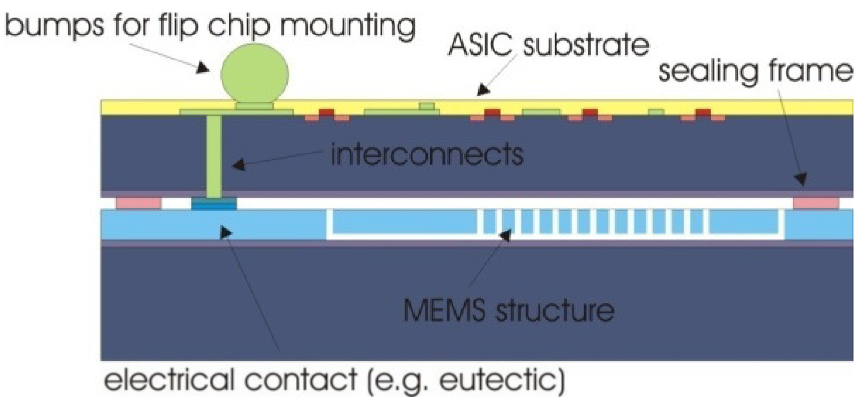
Metal interlayer based semiconductor wafer bonding

Joerg Froemel, Joerg Braeuer, Maik Wiemer, Esashi Masayoshi, Thomas Gessner

Outline

- Motivation
- Reactive Bonding
  - Theory
  - Reactive systems
- Near room temperature SLID (Solid Liquid Inter-Diffusion) bonding
  - Theory
  - Experiment and results
- Cooperation with Tohoku University

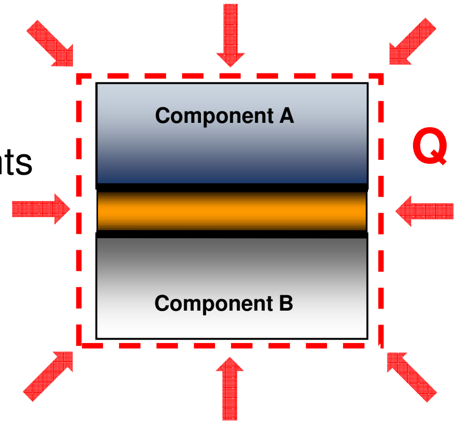
Motivation – Why metal based low temperature bonding?



- Temperature sensitive materials
- Mechanical, electrical connection
- Integration of LSI
- Heterogeneous materials

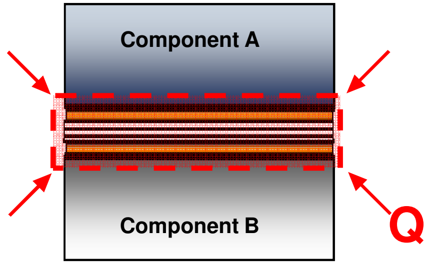
Conventional bonding:

- Heat up whole components (>300 ℃) → Thermo-mechanical stress
- Eutectic bonding…



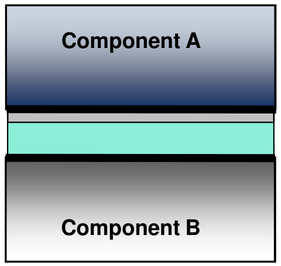
Internal heat source:

- Localized heating → Reduced thermo-mechanical stress
- → **Reactive bonding**



no heat source:

- No heating necessary→ no thermo-mechanical stress
- → **Ga based SLID bonding**



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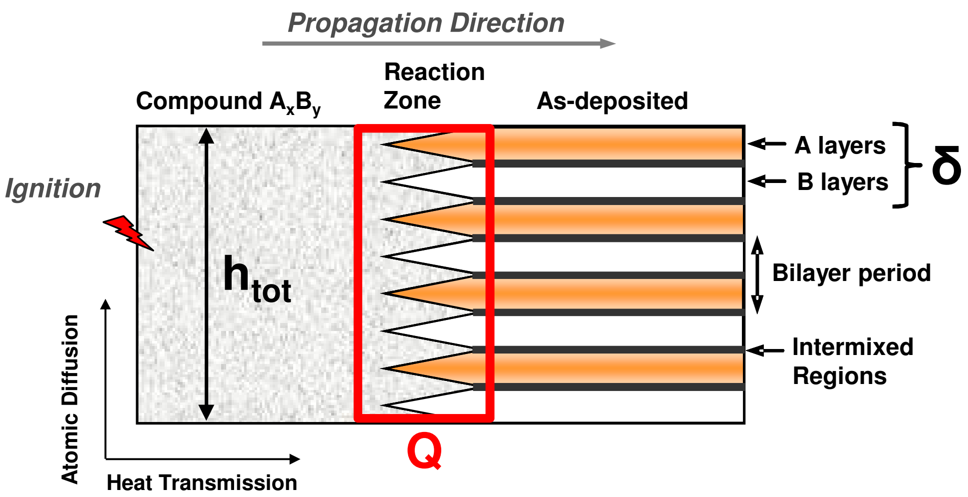
Theory

Reactive & Nano Scale Multilayer Systems – General

- Numerous nanometer thick layers alternating between two elements
- Reactants A and B (As-deposited) react exothermically during intermixing (Reaction Zone) and form products (Compound) » A + B → A B + **Q**
- Heat generation > removing by thermal diffusion → self-sustaining reaction
- Main geometry parameters: Bilayer period and total film thickness



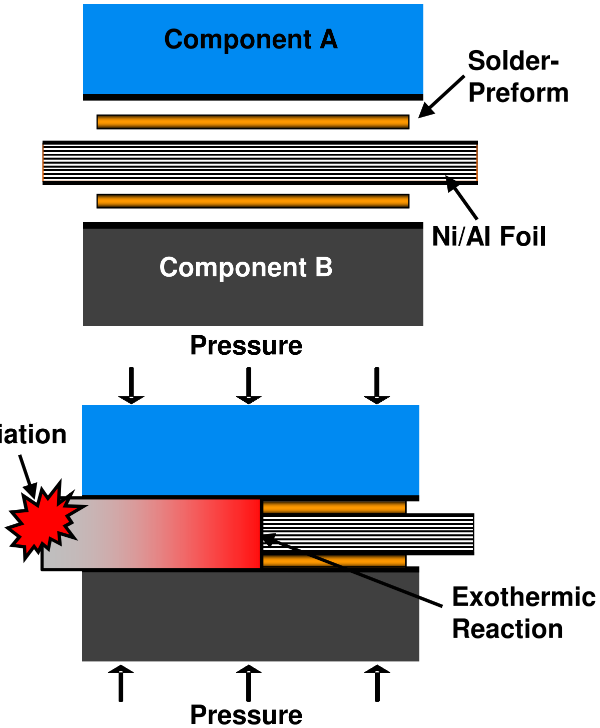
Properties:

- Reaction velocities up to 90 m/s
- High reaction temperatures (3000 °C)
- Local heating rate reaching 10^9 K/s
- No special environment needed (O_2, N_2…)
- Many materials possible (Al, Si, CuO etc.)

Reactive Systems @ Fraunhofer ENAS/ZfM

Reactive bonding with iRMS vs. NanoFoil© bonding

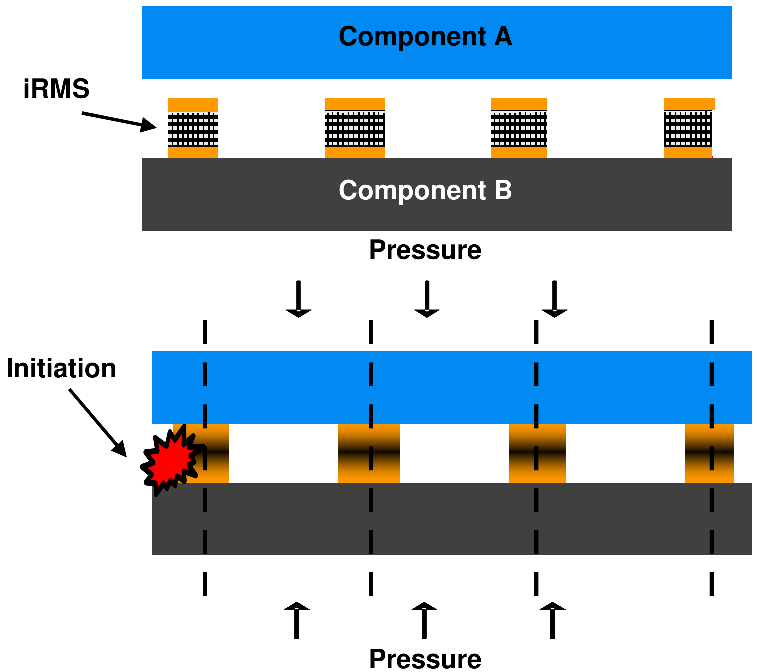
NanoFoil© bonding



Thickness: >20 µm Width: >1 mm

Number of individual layers: >1000

iRMS

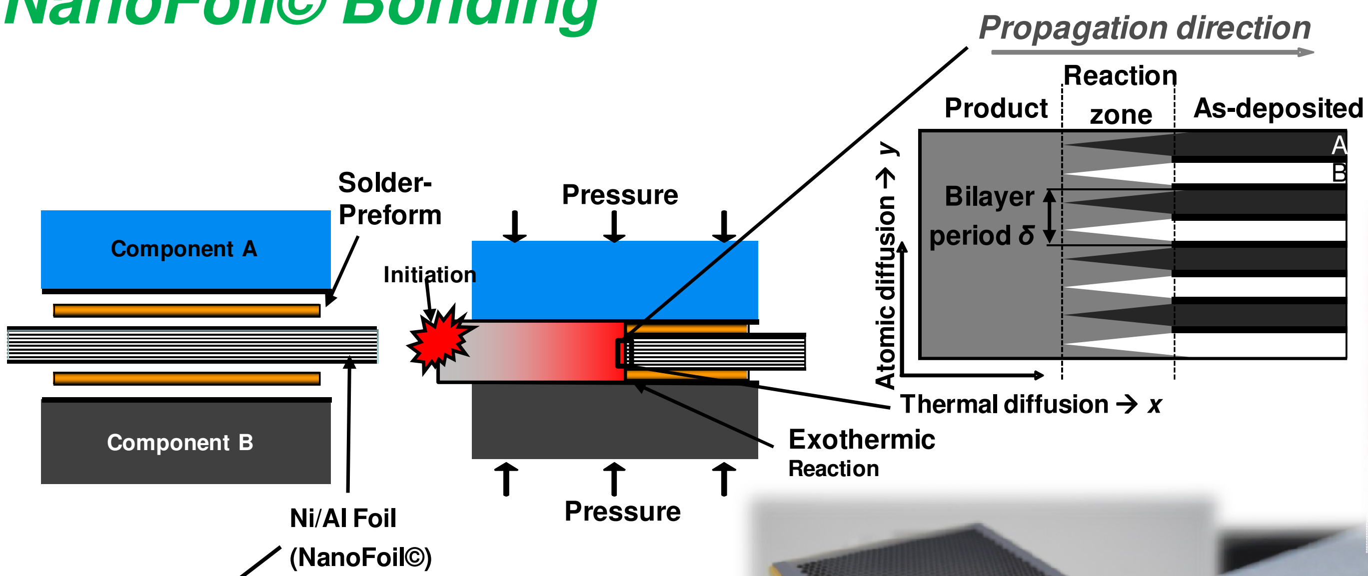


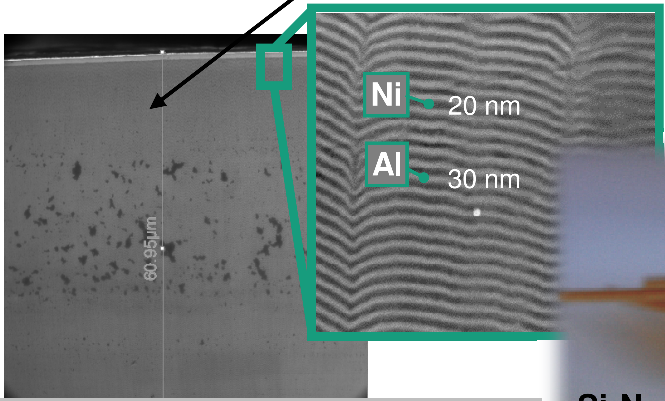
Thickness: <2.5 µm Width: <0.1 (0.5) mm

Number of individual layers: <50 (costs!!!)

Reactive Systems @ Fraunhofer ENAS/ZfM

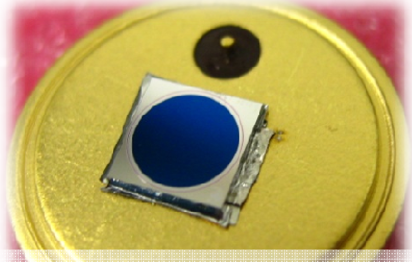
NanoFoil© Bonding



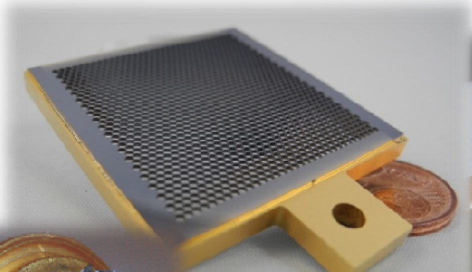


Individual layers within the nano scale!
> 1000 layers

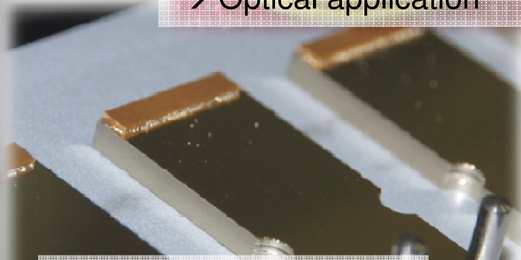
Steel – Quartz
[Mikrotechni&Sensorik]
→ Mechanical application



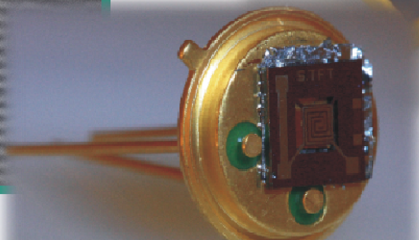
CaF – Covar [Silicon Sensors]
→ Optical application



Ni – Si [MIT, USA]
→ Space application



Cu – Ceramic [DILAS GmbH]
→ Laser application



Si_3N_4 – Covar [Siegert TFT]
→ Optical application

Demonstrators bonded @ ENAS (some examples!), but for wafer bonding and MEMS not similar applicable

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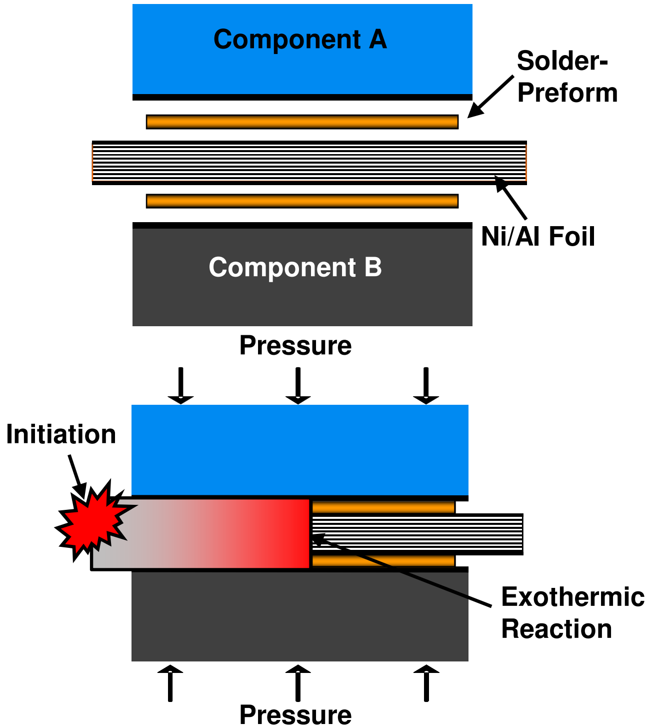
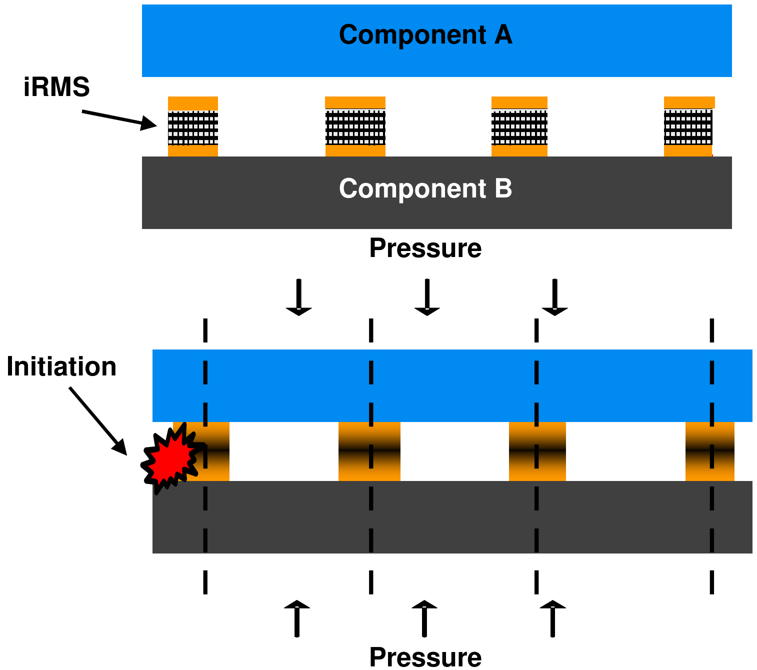
NanoFoil© bonding



Thickness: >20 µm Width: >1 mm

Number of individual layers: >1000

iRMS



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Number of individual layers: <50 (costs!!!)

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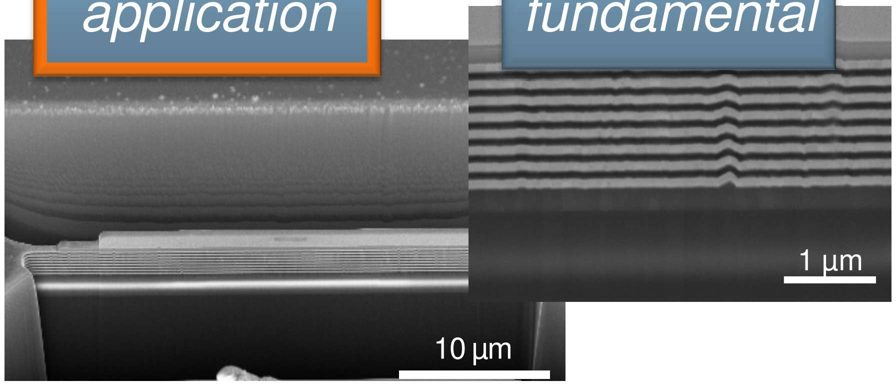
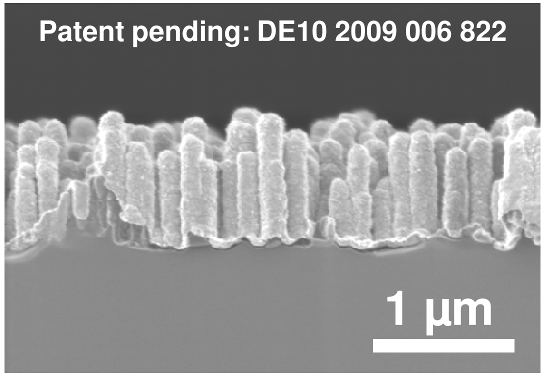
iRMS @ Fraunhofer ENAS/ZfM

Overview

- Integrated **R**eactive **M**aterial **S**ystems (iRMS)
  - Multilayer
    - PVD *application*
    - ECD *fundamental*
  - Vertical *fundamental*
  - Others *fundamental*





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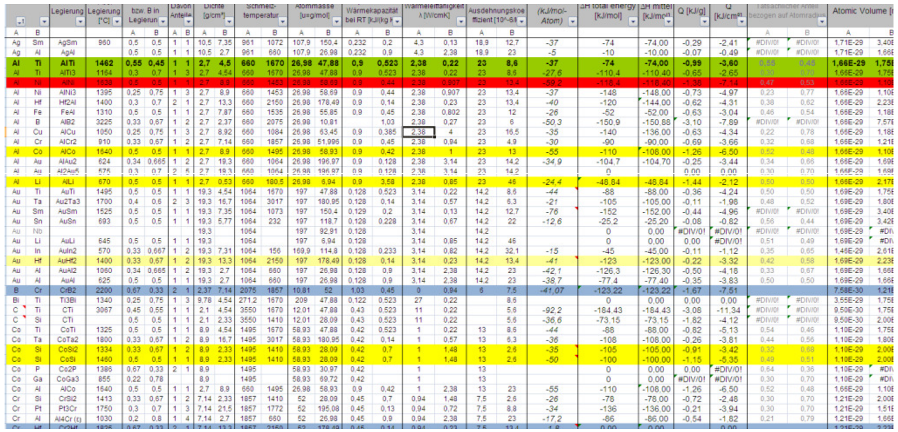
iRMS @ Fraunhofer ENAS/ZfM

Energetic classification

- **Integrated <u>R</u>eactive <u>M</u>aterial <u>S</u>ystems (iRMS)** → different reactants possible → uniform classification needed

→Heat of formation ΔH!

- Data base with nearly all combinations within the periodic table of elements developed



I. Low energetic systems: ΔH: 30…59 kJ/mol-Atom → Al/Co, <u>Al/Ti</u>…

II. Medium energetic systems: ΔH: 60…89 kJ/mol-Atom → Ni/Si, <u>Ti/Si</u>…

III. High energetic systems: ΔH: > 90 kJ/mol-Atom → Ti/B, <u>Al/Pd</u>…

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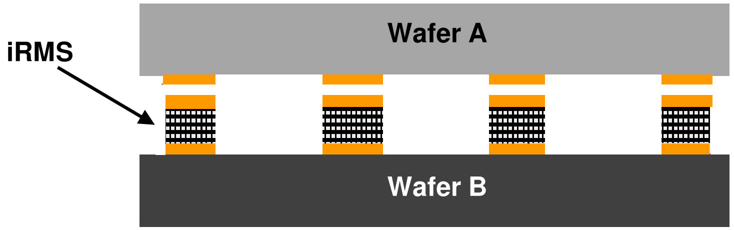
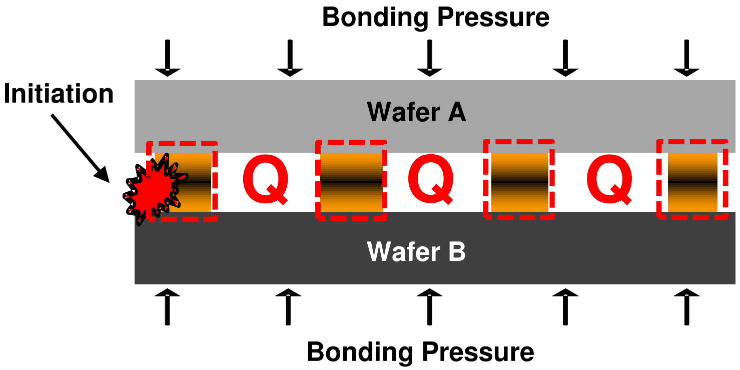
iRMS @ Fraunhofer ENAS/ZfM

Process flow for reactive bonding

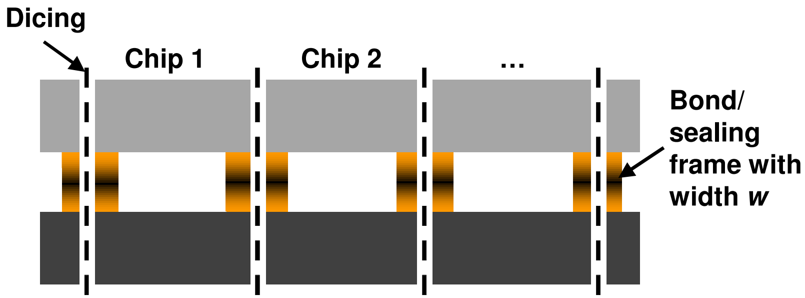
Preparation of bonding partner (Wafer A), e.g. bonding layer, and deposition / patterning (PVD) of iRMS (Wafer B)



Wafer bonding @ room-temperature: wafer alignment, evacuation, applying pressure, ignition of reaction (**Patent pending: DE10 2009 006 822 B4; JP, US and EP has filed**)

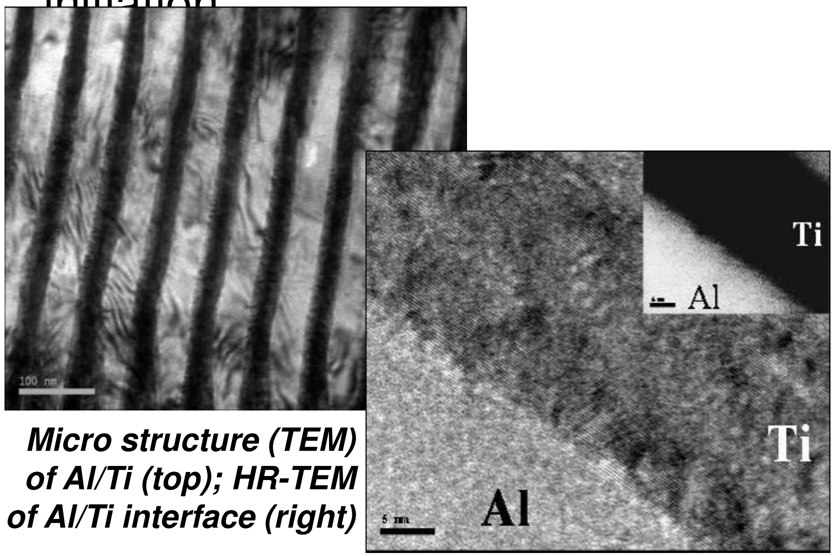


Immediately after wafer bonding: wafer pairs can be further processed



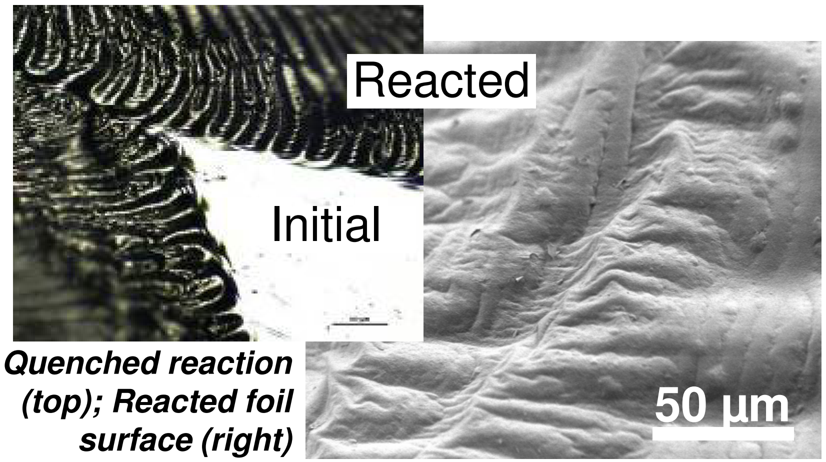
Low energetic iRMS
Overview

- Max. 100 individual layers
- Ignition methods: spark, laser…
- No self-sustaining reaction directly onto substrates → reaction is quenched immediately after initiation



Micro structure (TEM) of Al/Ti (top); HR-TEM of Al/Ti interface (right)

- Self-propagating reactions in freestanding foils possible (more than 2 µm overall thickness necessary)
- Reaction velocities ranging from 0.05 m/s to 0.25 m/s
- **Wafer bonding not possible!**

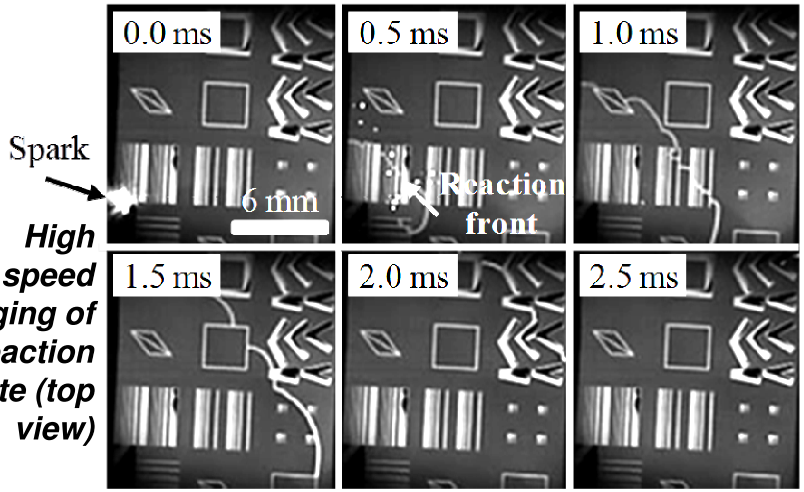


Quenched reaction (top); Reacted foil surface (right)

Medium energetic iRMS

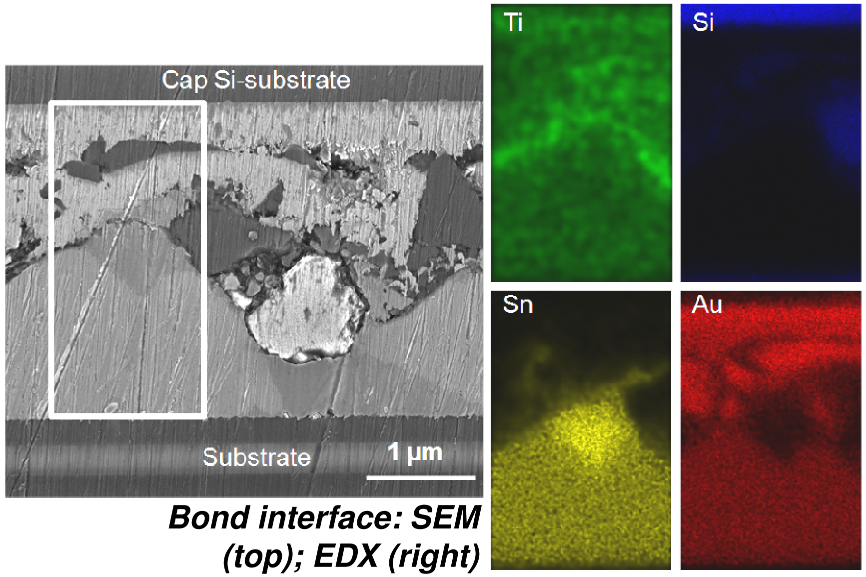
Overview

- Max. 70 individual layers (deposition process relatively complex)
- Patterning via wet etching possible ("Bell etchant" (H_2O, NH_4F, HNO_3))
- Self-sustaining reactions initiated (reaction velocities ranging from 6 m/s to 10 m/s)



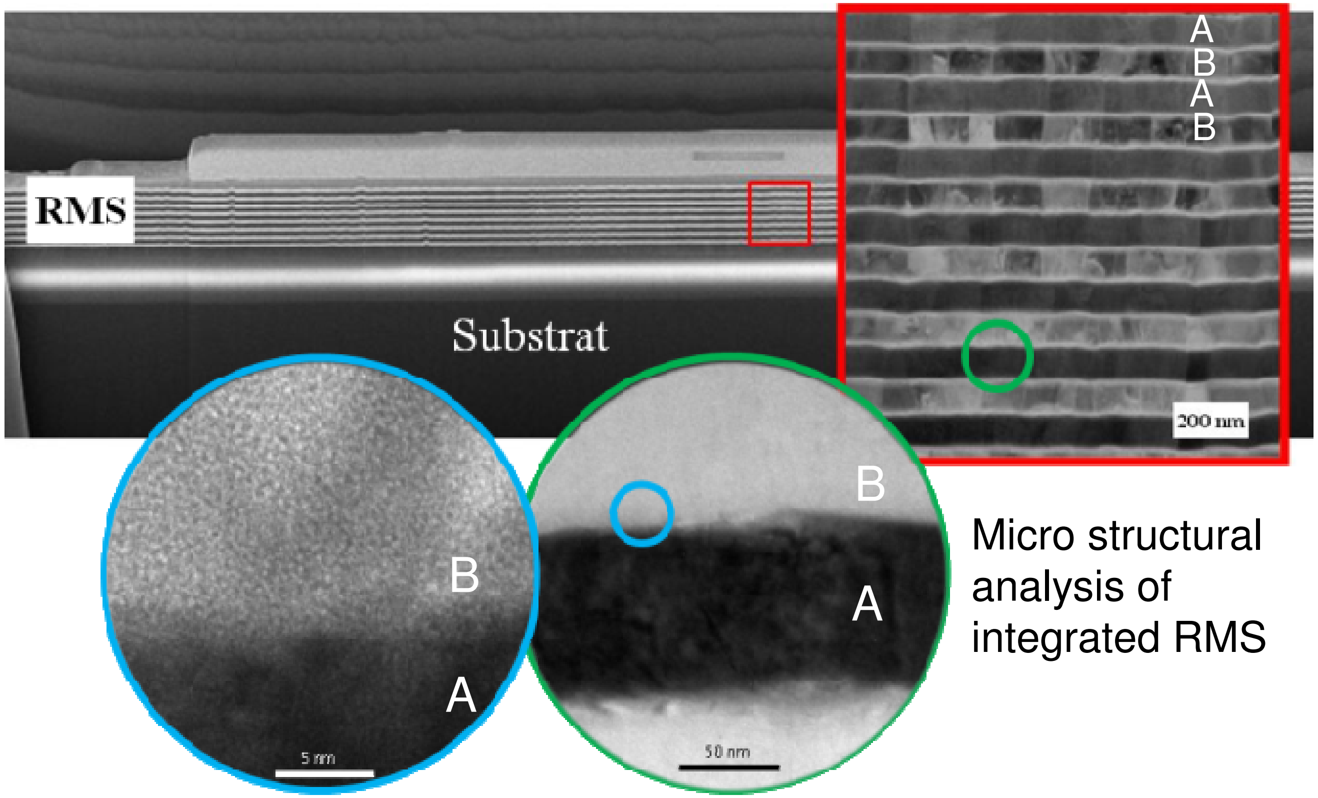
High speed imaging of reaction route (top view)

- Self-sustaining reactions very "explosive" → substrate damaged → carefully choosing the adhesion layer
- **Wafer bonding possible, but reaction product very brittle**



Bond interface: SEM (top); EDX (right)

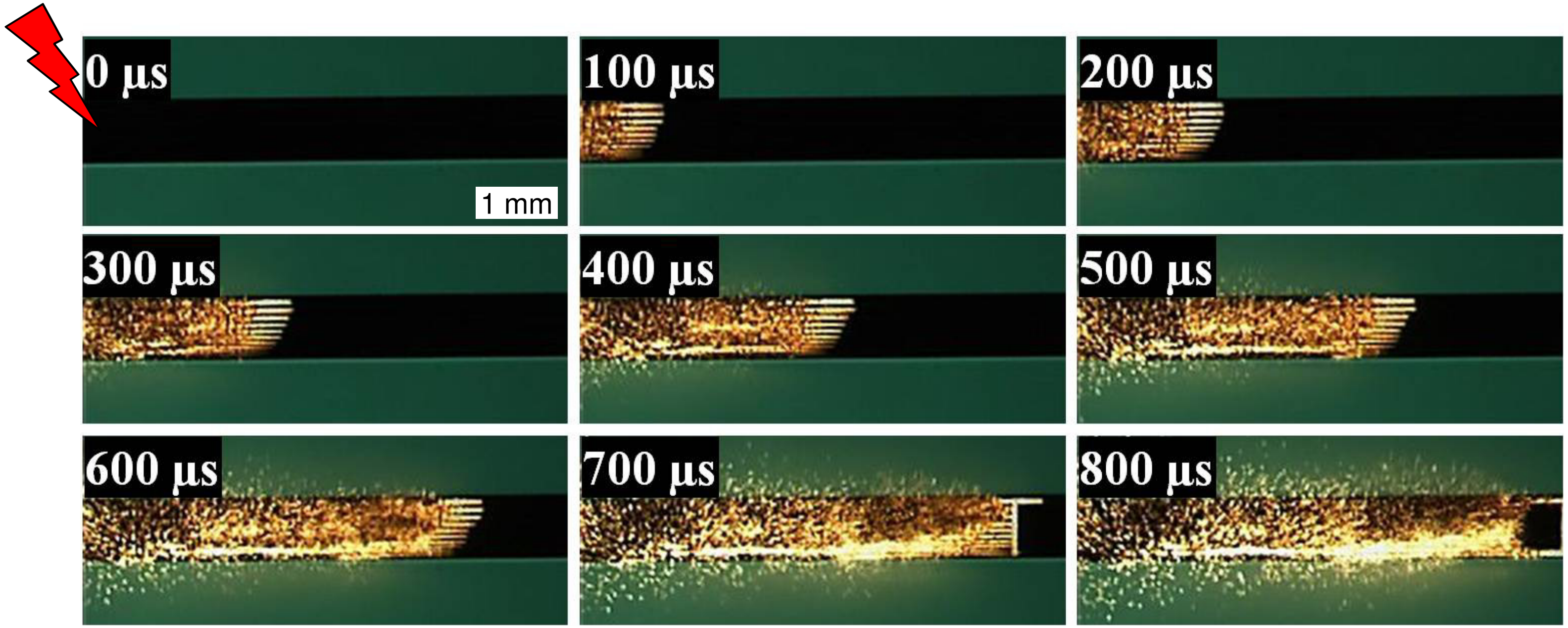
High energetic iRMS
Micro structural analysis



Micro structural analysis of integrated RMS

- Micro structural analysis of high energetic RMS → interdiffusion zone influences reaction properties
- RMS with sharp interfaces → no significant intermixing occurred during deposition (interdiffusion zone appr. 2-3 nm)

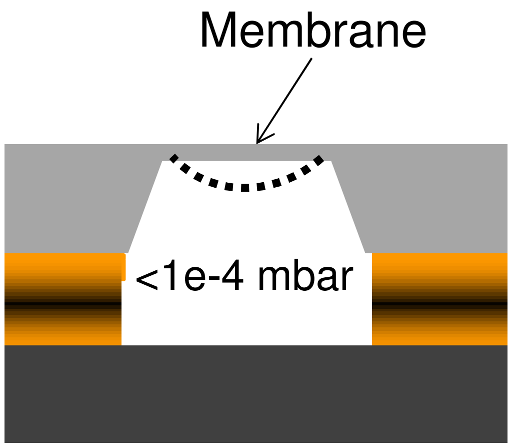
High energetic iRMS
High-Speed-Analysis (I)



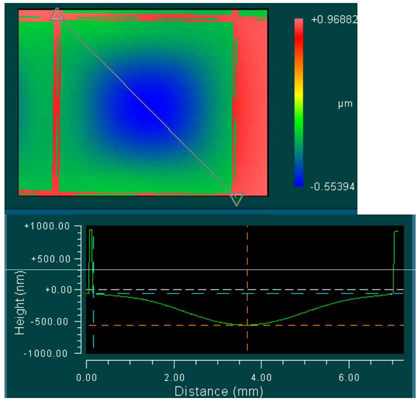
High-speed time lapse images showing the reaction propagation from left to right; timestamp is relative to the first image in the sequence

- Substrate before dicing: 6” Si-Wafer/SiO_2 (1 µm thickness)
- 20 µm … 500 µm line width tested
- Initiation via probe tips at room-temperature (atmosphere), frame rate 30‘000 fps
- **25 m/s reaction velocity → independent on frame width**

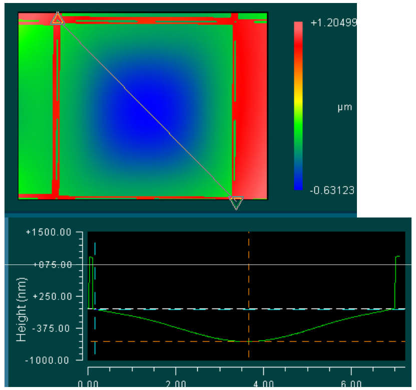
High energetic iRMS
Reactive wafer bonding – Hermiticity testing



Membrane bow via WLI



Membrane bow
after bonding:
512 nm



Membrane bow
after 90 days:
504 nm

- Membrane bow independent on:
  - Storage time
  - Bond frame width (50 µm … 500 µm)
- Exact determination of leakage rate? → no leakage detected via He leakage test (< 1e-8 mbar-l/s)

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  - Reactive systems
- Near room temperature SLID (Solid Liquid Inter-Diffusion) bonding
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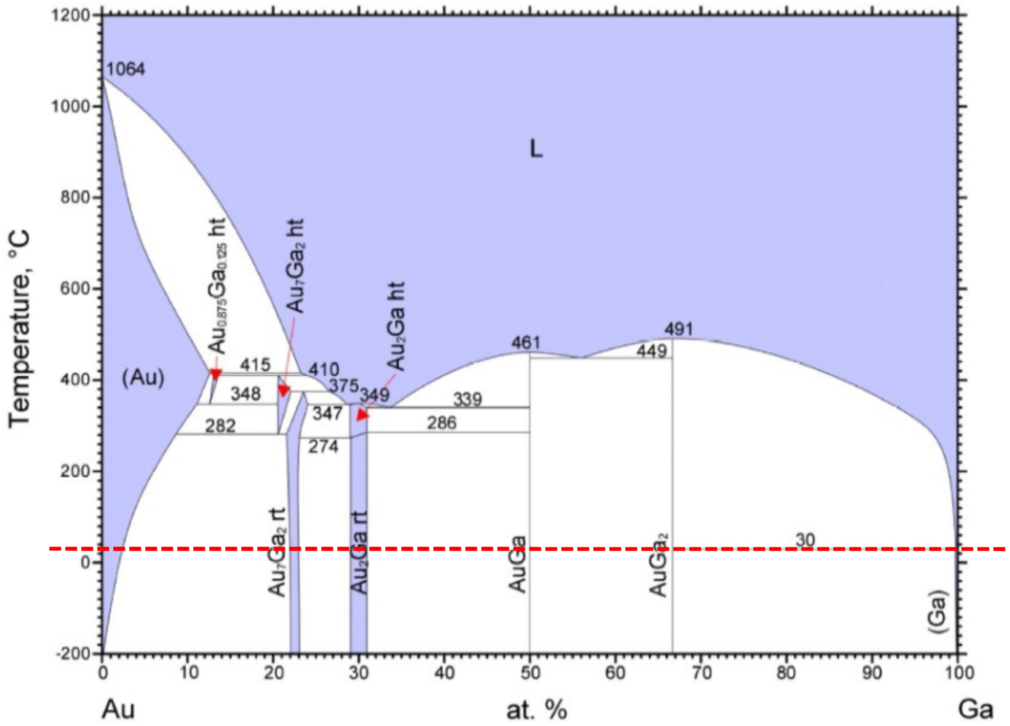
Gallium based bonding

Overview and principle (Au/Ga)



- Metal with low melting point

-> gallium

- Metal with high melting point

-> gold

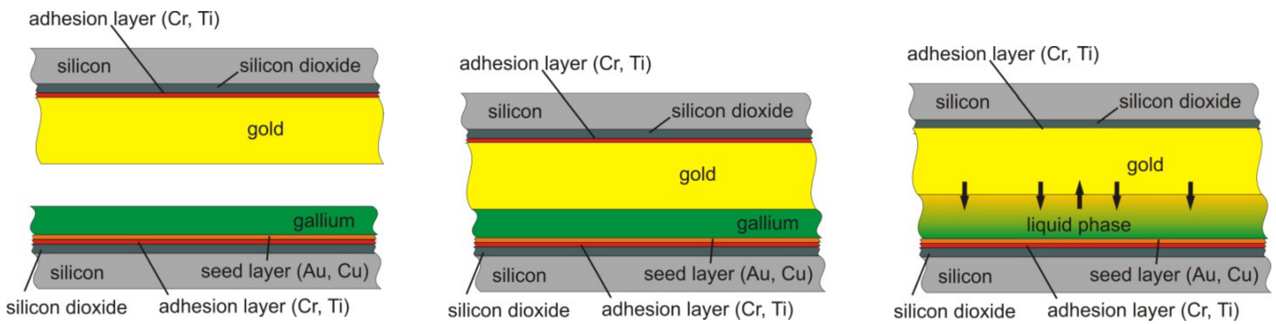
- Phase transformation of the liquid metal (at process temperature) to a higher melting point material

-> AuGa2, AuGa, Au2Ga, Au7Ga2

Process temperature: 30°C, melting point of resulting material > 491°C (Au2Ga)

Gallium based bonding
Overview and principle (Au/Ga)

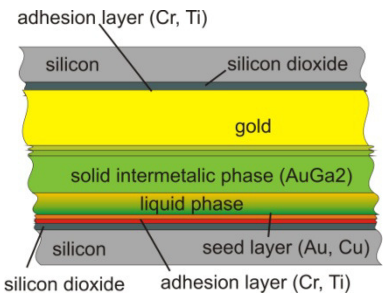
Initial setup	wetting	Liquid diffusion and alloying
Gold and gallium layers are prepared on substrate by deposition	Because of physical contact gallium wets surface of gold	Gold diffuses into liquid gallium until saturation

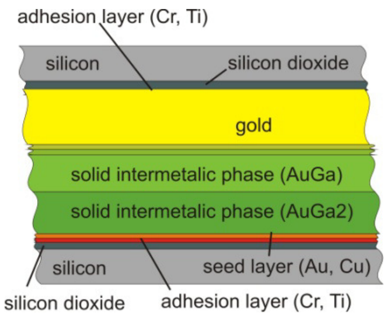


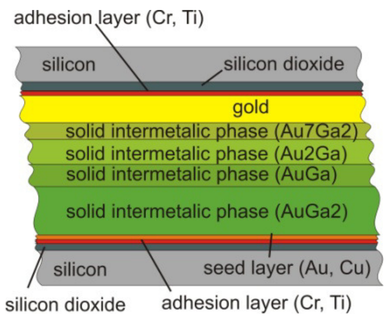
Gallium based bonding

Overview and principle (Au/Ga)

Gradual solidification	Solidification finished	Solid-Diffusion
The bond gradually solidifies by forming high melting point components	The bond is completely solidified and all liquid disappeared	Further diffusion in the solid driving the reaction to reach equilibrium







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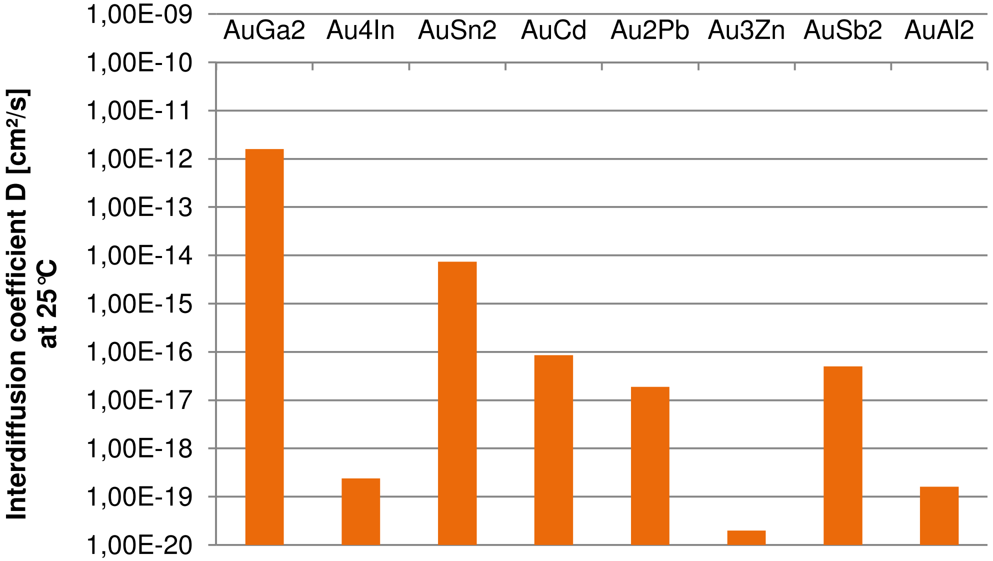
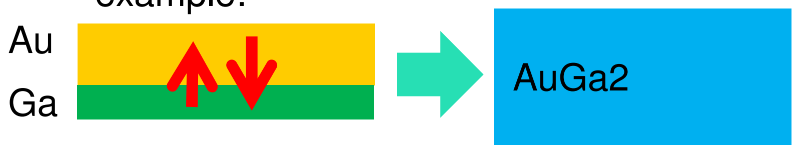


V.Simic and Z.Marinkovic, *Thin Solid Films*, 34 (1976) 179

Interdiffusion coefficient:

characterizes speed of diffusion process from separate materials until complete formation of alloy

example:



AuGa2: D (25°C) = $1.6 \cdot 10^{-12}$ cm²/s

2nd Fick's law:

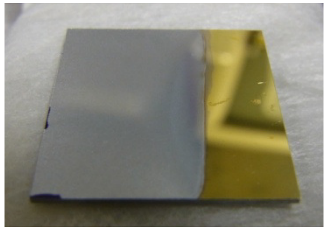
$$\frac{dc}{dt} = D\frac{dc^2}{dx^2} \qquad \langle x^2 \rangle = \frac{A}{N}\int_{-\infty}^{+\infty} x^2 c(x,t)\,dx = 2Dt$$

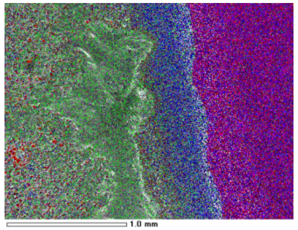
In the case of 500 nm AuGa2 at 25°C:

13 min!

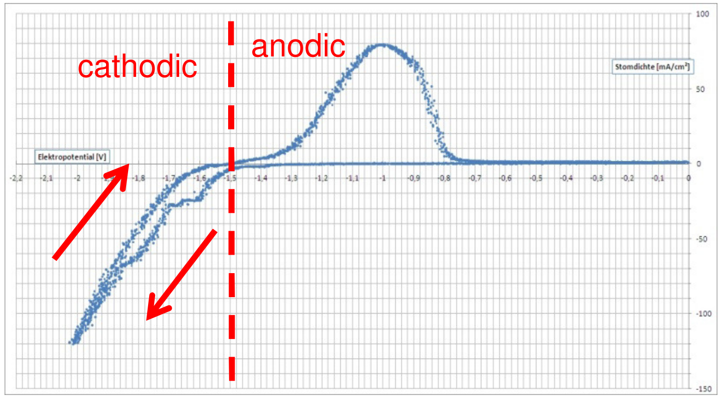
(AuIn : 289 days)

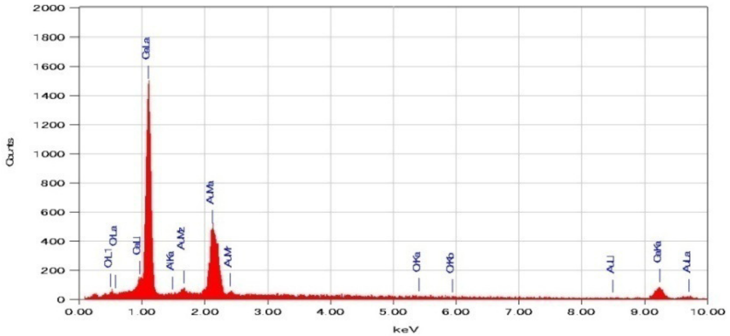
Gallium deposition
Electroplating





EDX:
red = Si
blue = Au
green = Ga

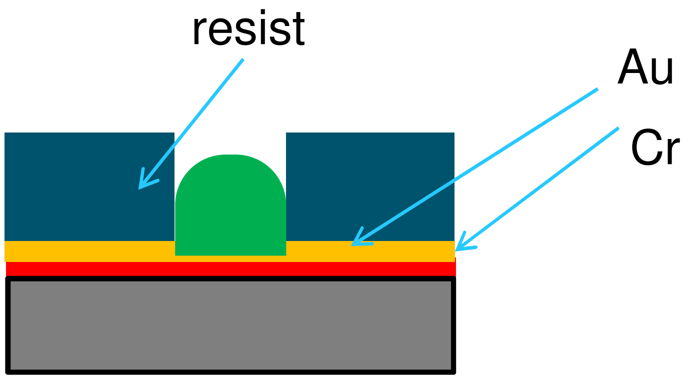


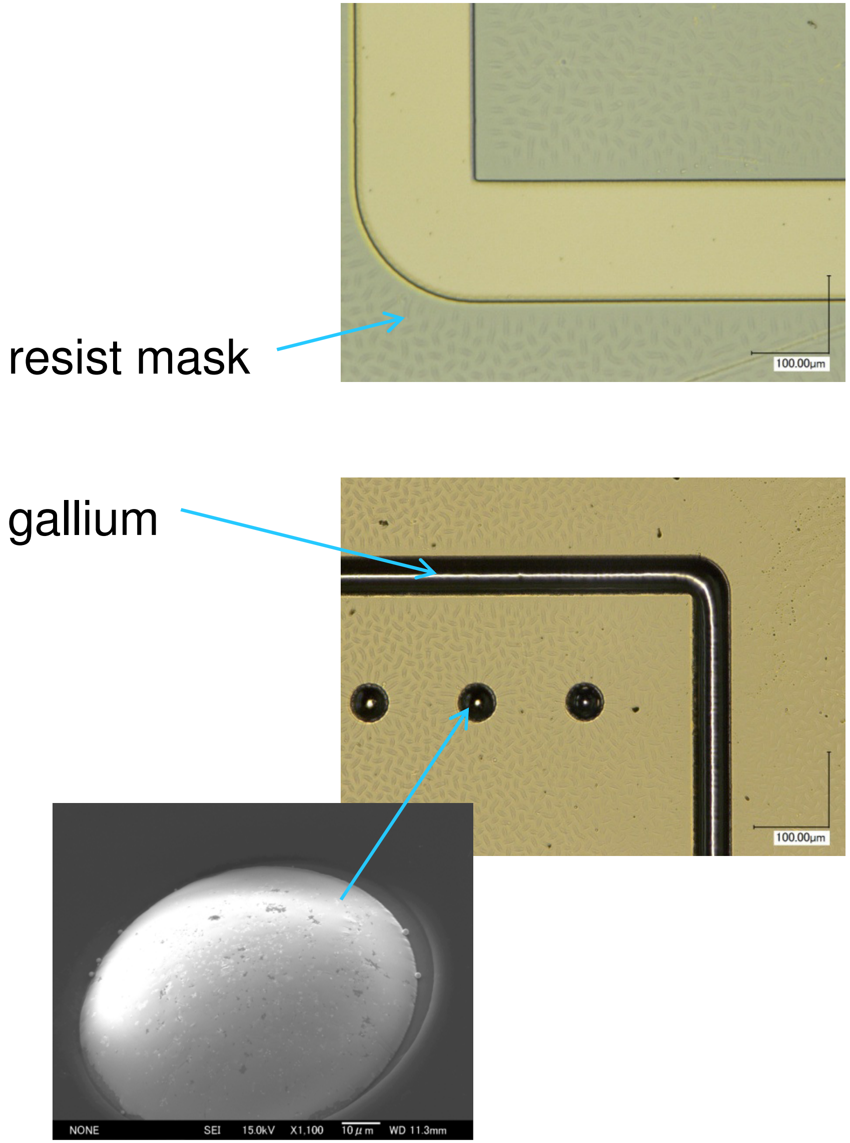


元素	(keV)	質量%	誤差%	原子数%	化合物	質量%	カチオン数	K
Al K	1. 486	0. 01	0. 15	0. 05				0. 0090
Cr K								
Ga K	9. 241	59. 11	2. 95	80. 30				71. 1652
Au M	2. 121	40. 87	0. 48	19. 65				28. 8258
合計		100. 00		100. 00				

- Electrolyte based on GaCl3
- Au, Pt, Cr and Cu tested as seed layers

Gallium deposition
Electroplating





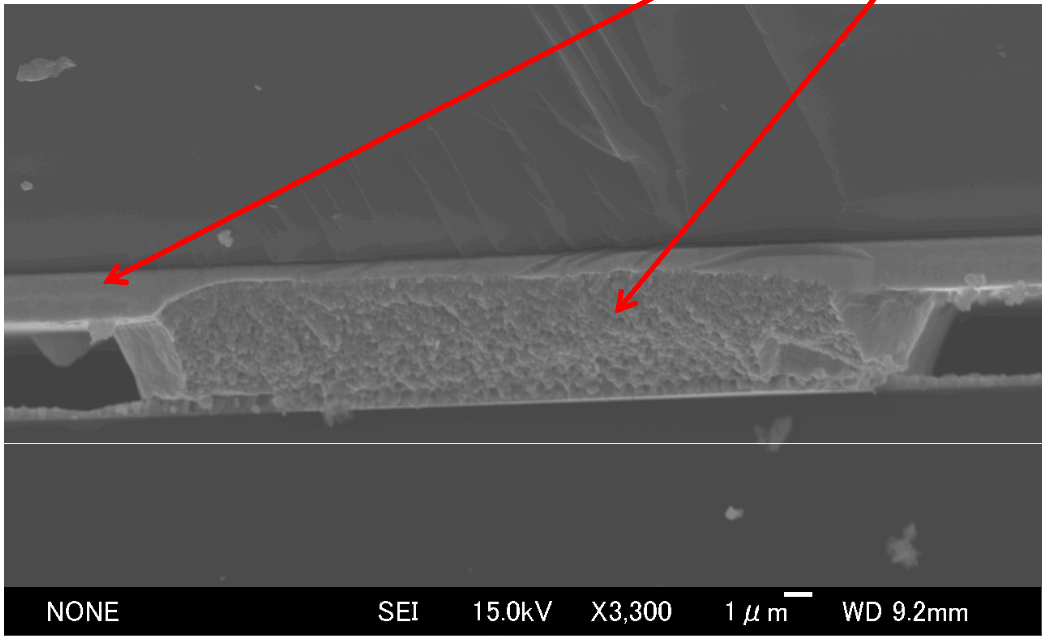
- Deposition in a mask of negative photoresist
- Etching of seed layer after resist removal

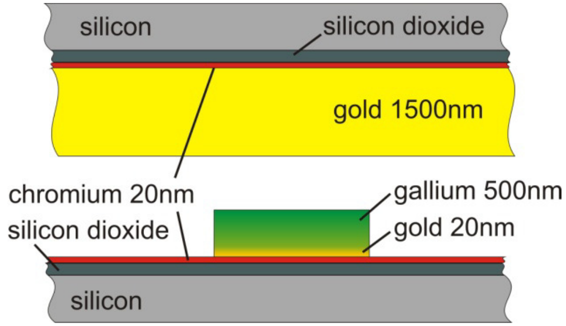
Gallium SLID bonding

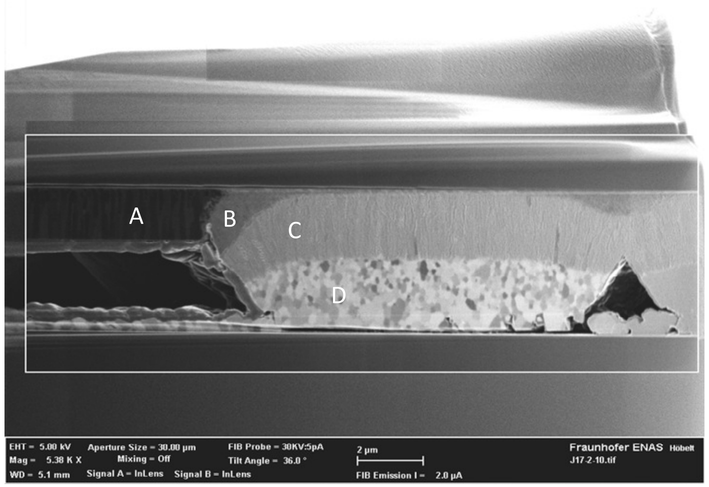
bonding experiment

Au

Au/Ga alloy







- Temperature: 30℃
- Mechanical pressure: 150kPa
- Time: 20 min

- bonding could be achieved
- Au is partly consumed, Ga is completely consumed

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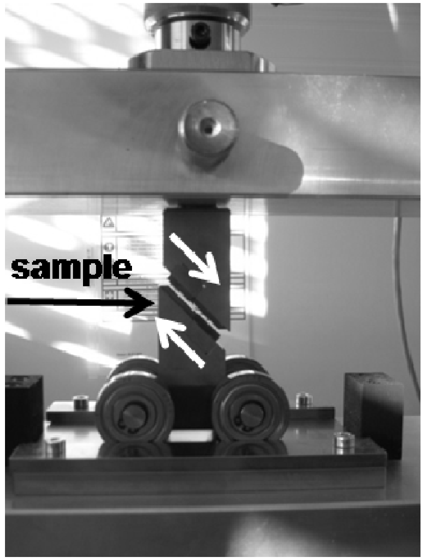
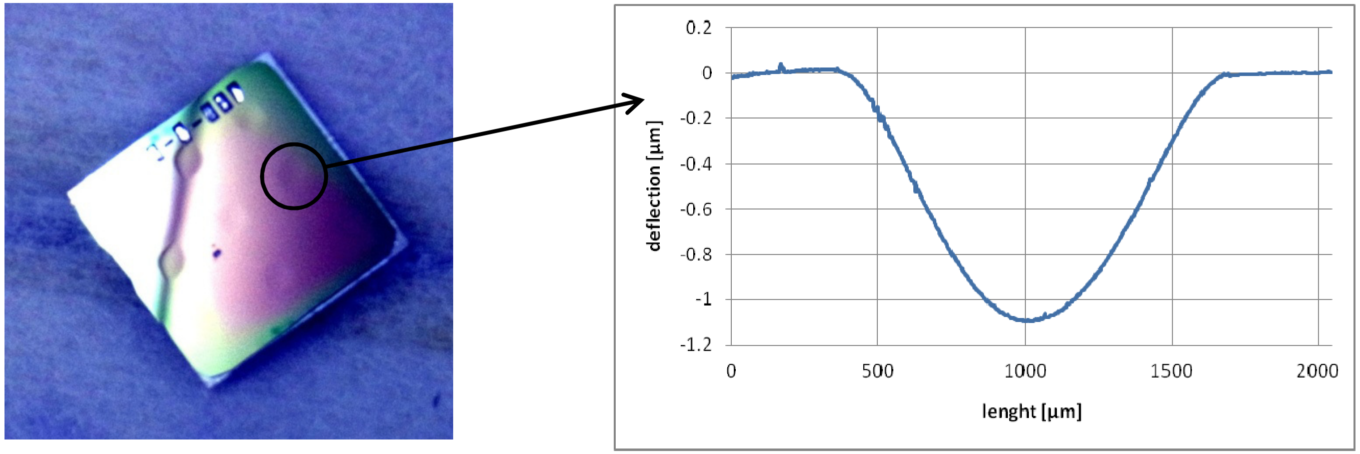
Gallium SLID bonding
bonding experiment



Properties after bonding (room temperature)

- Electrical resistance 2mOhm/cm²
- Shear strength >42MPa
- Hermetic



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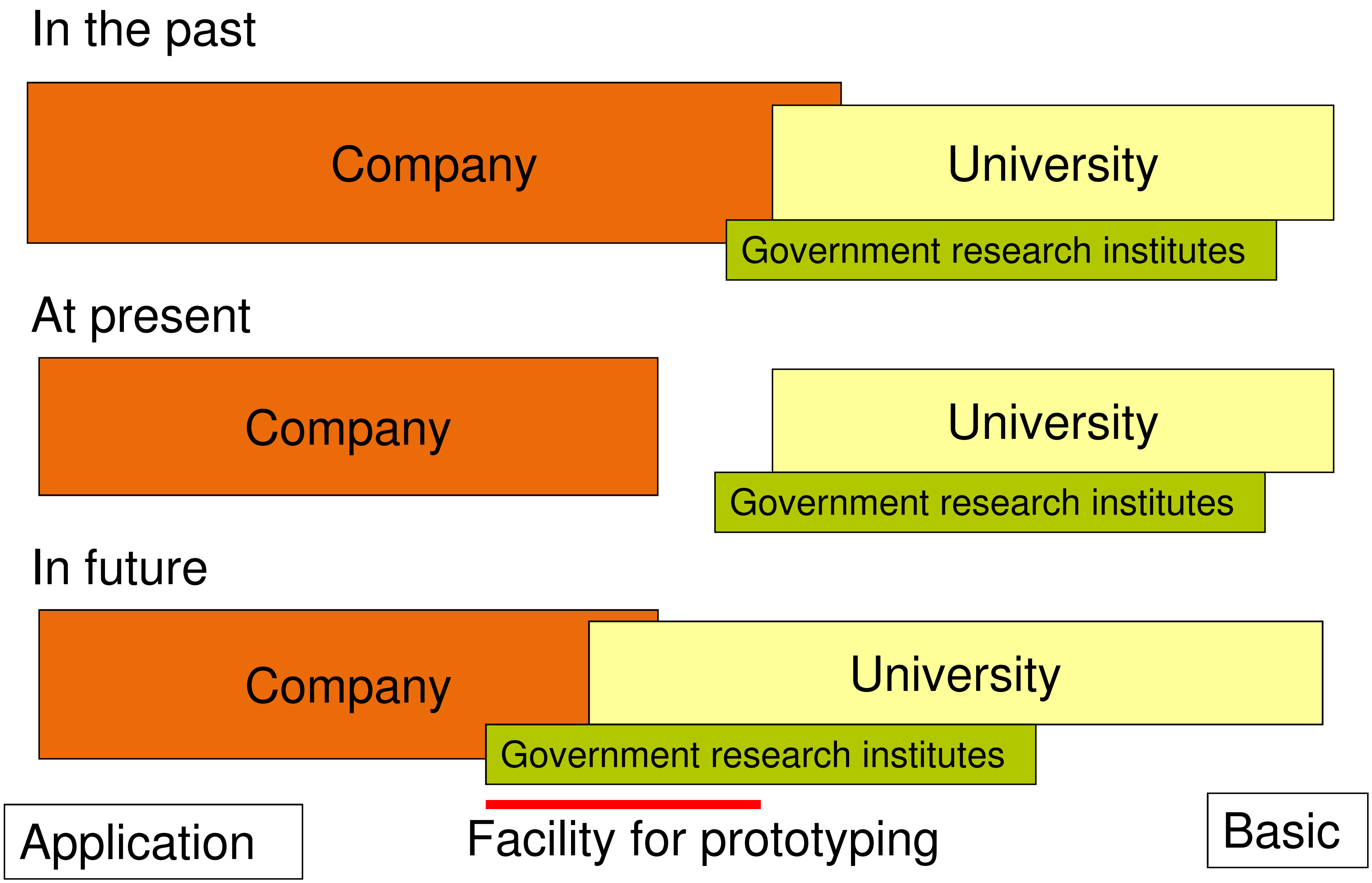
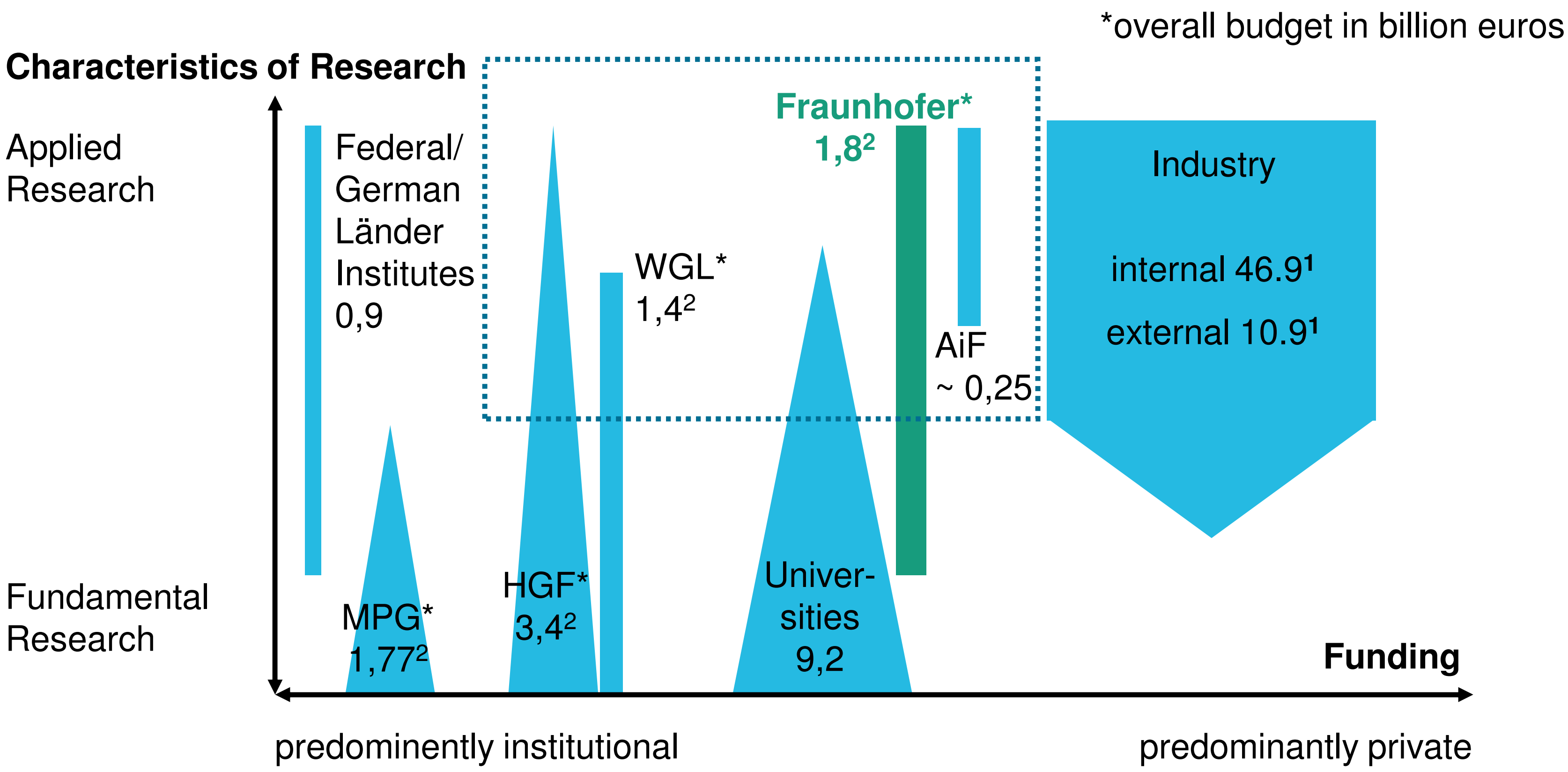
The Japanese Research Landscape



The German Research Landscape



HGF Hermann von Helmholtz-Gemeinschaft
WGL Wissenschaftsgemeinschaft Gottfried Wilhelm Leibniz
AiF Arbeitsgemeinschaft industrieller Forschungsvereinigungen
MPG Max-Planck-Gesellschaft

[1] estimation Wissenschaftsstatistik 2010, Stifterverband

[2] 2011

Source:
Stifterverband für die Deutsche Wissenschaft, Destatis, research organizations

Cooperation with Tohoku University

Fraunhofer Project Center NEMS-/MEMS-Devices and Manufacturing Technologies at Tohoku University

Prof. Thomas Gessner

Prof. Masayoshi Esashi

- Started: April 1st, 2012
- Partners: Fraunhofer and Tohoku University
- Affiliation: WPI-AIMR, Tohoku University

  World Premier International Research Center Initiative Advanced Institute for Materials Research, Tohoku University, Sendai Japan
- Location: Esashi Laboratory

  Aobayama campus of Tohoku University

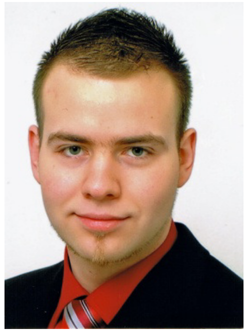

Thomas Gessner


Masayoshi Esashi

Fraunhofer Project Center NEMS-/MEMS-Devices and Manufacturing Technologies at Tohoku University
In cooperation with

Fraunhofer


Jörg Frömel


Florian Kurth

Fraunhofer ENAS will send researchers frequently to Tohoku University.

Together with engineers and scientists from Tohoku University cooperative research on interesting topics is being conducted.

Purpose:

- Frontier research together with excellent researchers of Tohoku University (e.g. amorphous metals, room temperature wafer bonding)
- Exchange of research results to create application out of basic research (e.g. MEMS active elements from amorphous metal)
- Creating intellectual property from the aforementioned research than can be used and licensed by all partners
- Support of ongoing cooperation research projects of Fraunhofer ENAS with Japanese industry
- Help Japanese industry to acquire new opportunities for cooperation

Thank you for your attention!

Contact:
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