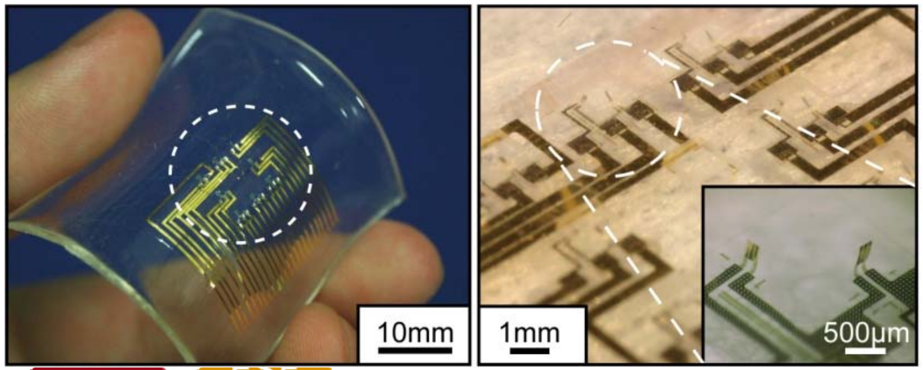
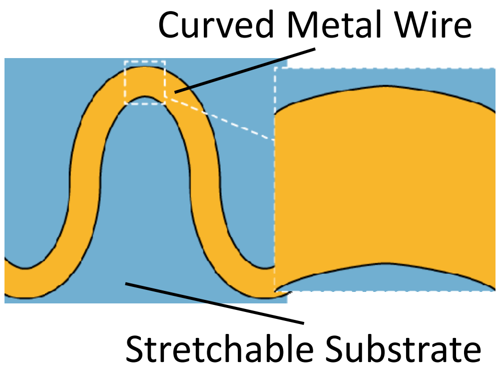
Flexible devices using rigid materials

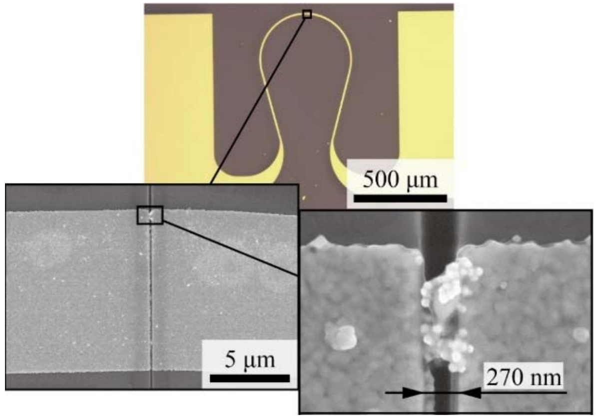
Eiji Iwase (Waseda University)

Outline of my talk:

- **Importance**: Flexibility on energy components
- **Difference**: Bendability and stretchabiliy
- **Challenge**: High performance and highly stretchable device







Importance : Flexible energy components

Energy generator
(ex. solar cells, thermoelectric generators)

Flexible organic solar cell

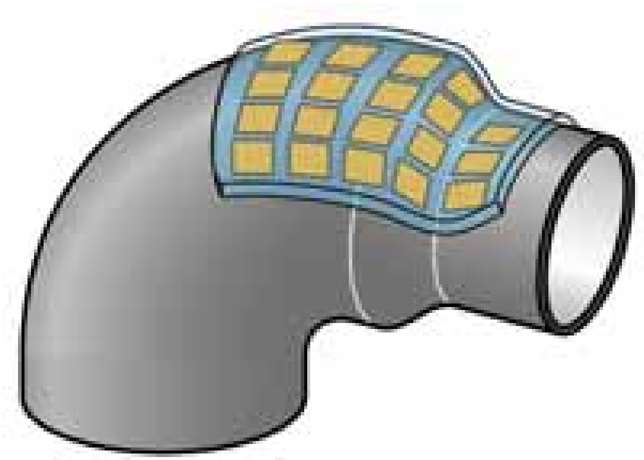
M. Kaltenbrunner *et al.*, *Nat. Commun.* (2012)

Bendable CNT-based thermo-electric generator

K. Suemori *et al.*, *Appl. Phys. Lett.* (2013)

Bendable thermoelectric generator on a glass fabric

S. J. Kim *et al.*, *Energy Environ. Sci.* (2014)

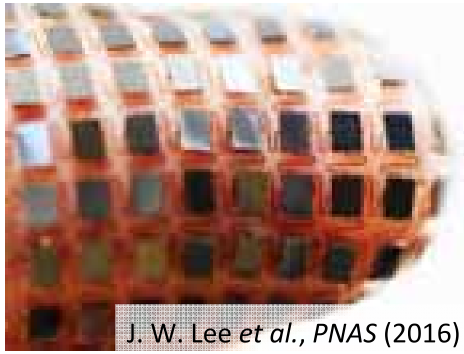


Energy storage
(ex. Lithium-ion batteries)

Stretchable Lithium-ion battery

S. Xu *et al.*, *Nat. Commun.* (2013)

Lithium-ion battery sheet

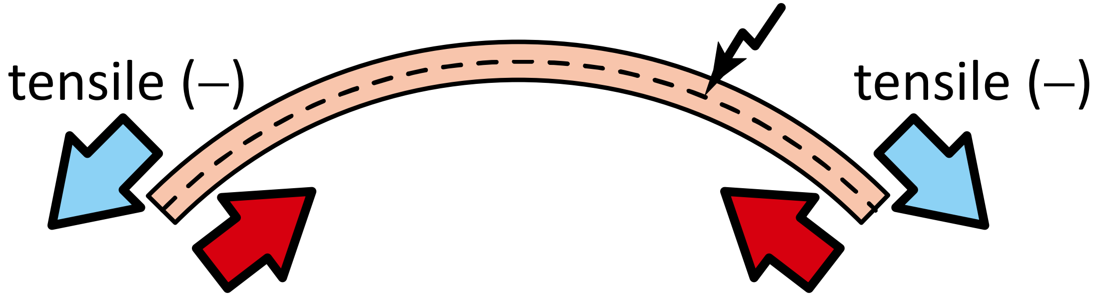


J. W. Lee *et al.*, *PNAS* (2016)

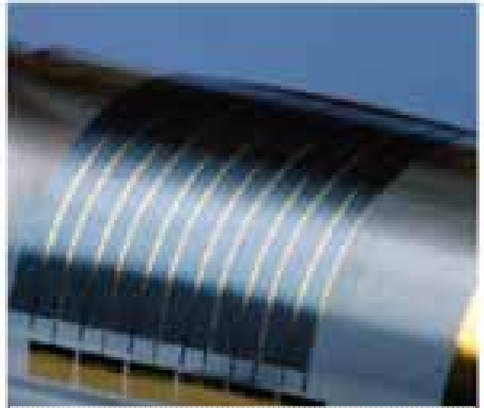
To use on any curved surface, flexibility is very important!

Difference: Bendability and stretchability

(i) Bending deformation



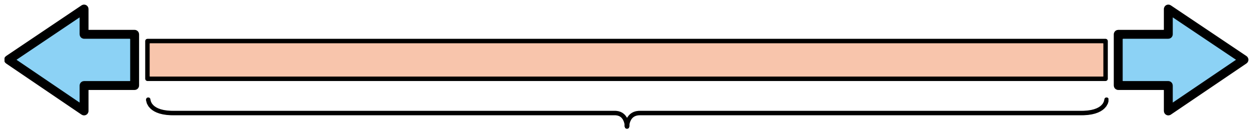
Ultrathin silicon solar cells



J. Yoon *et al.*, *Nature Materials* (2008)

→ **Thin device can have a bendability**

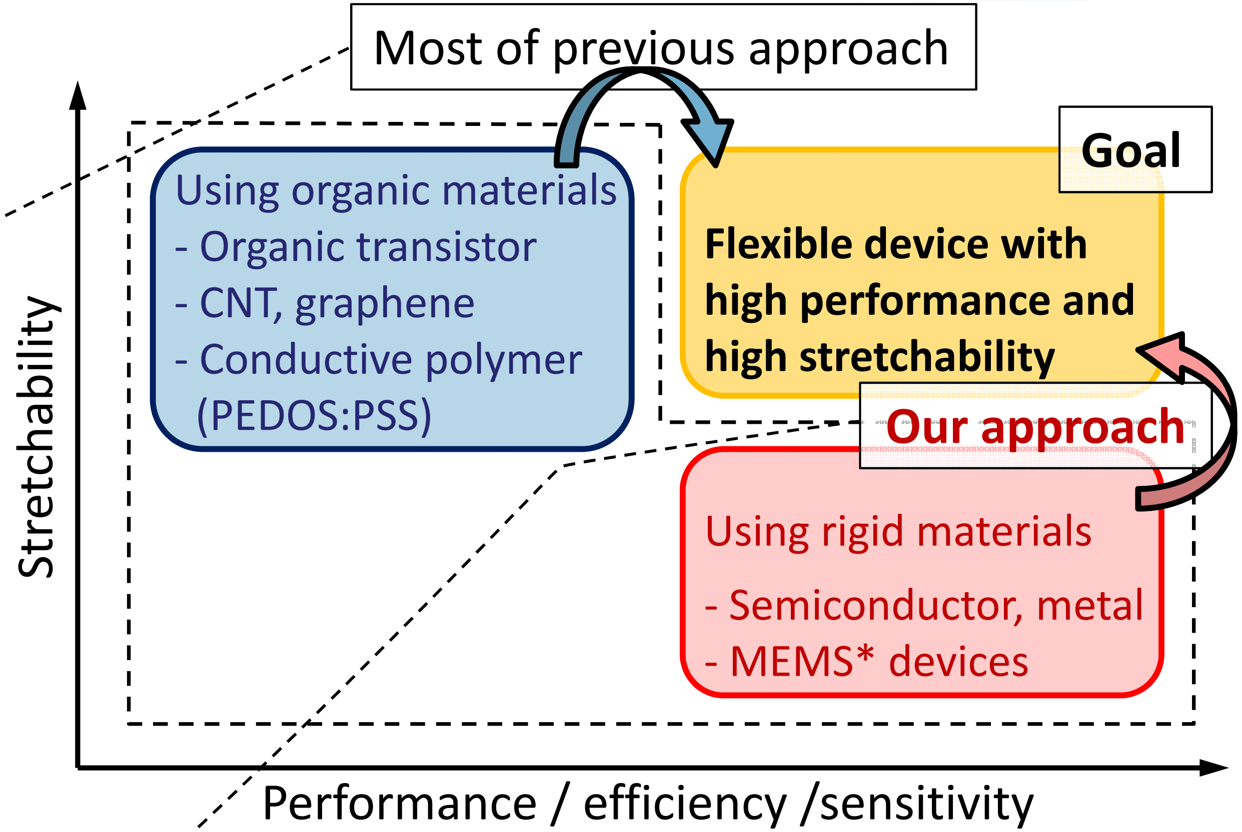
(ii) Stretching deformation



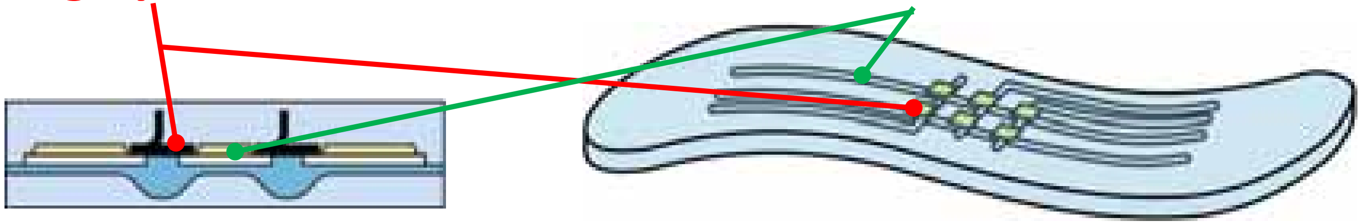
→ **There is no obvious solution to avoid a fracture**

Stretchablity is a challenging and important issue on flexible device

Challenge: Approach for stretchable device



Rigid & high performance device + **Stretchable wire**



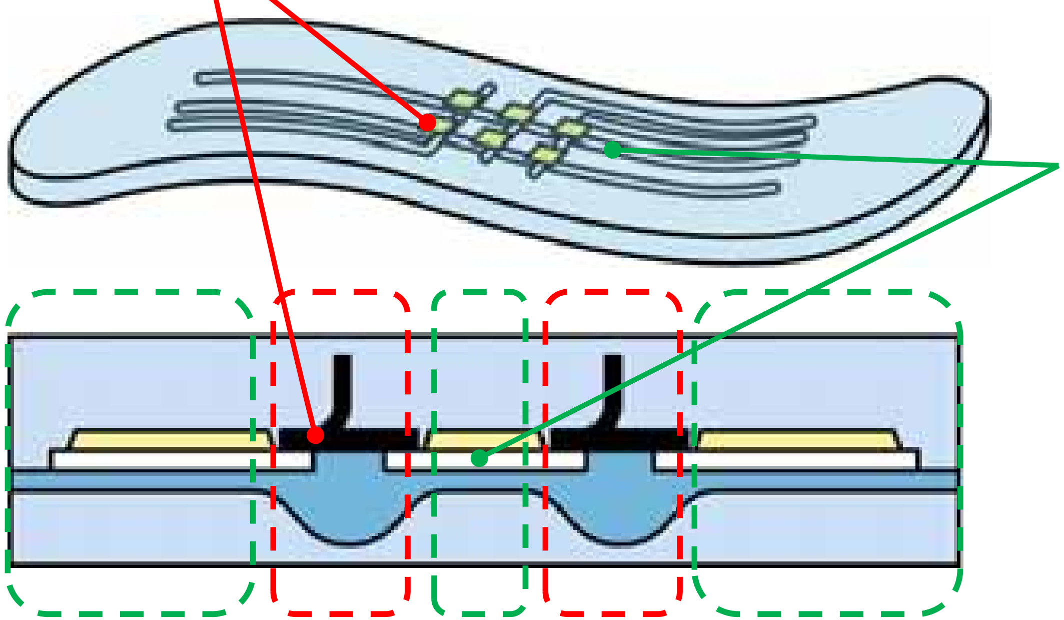
*MEMS = Micro-Electro-Mechanical Systems
= Tiny (< 1 mm) electric sensor/actuator

Challenge: Approach for stretchable device

Rigid & high performance device + Stretchable wire

Functional part
- Using MEMS devices or Silicon chips (for high performance or sensitivity)
- No deformation

1. Stamping transfer method



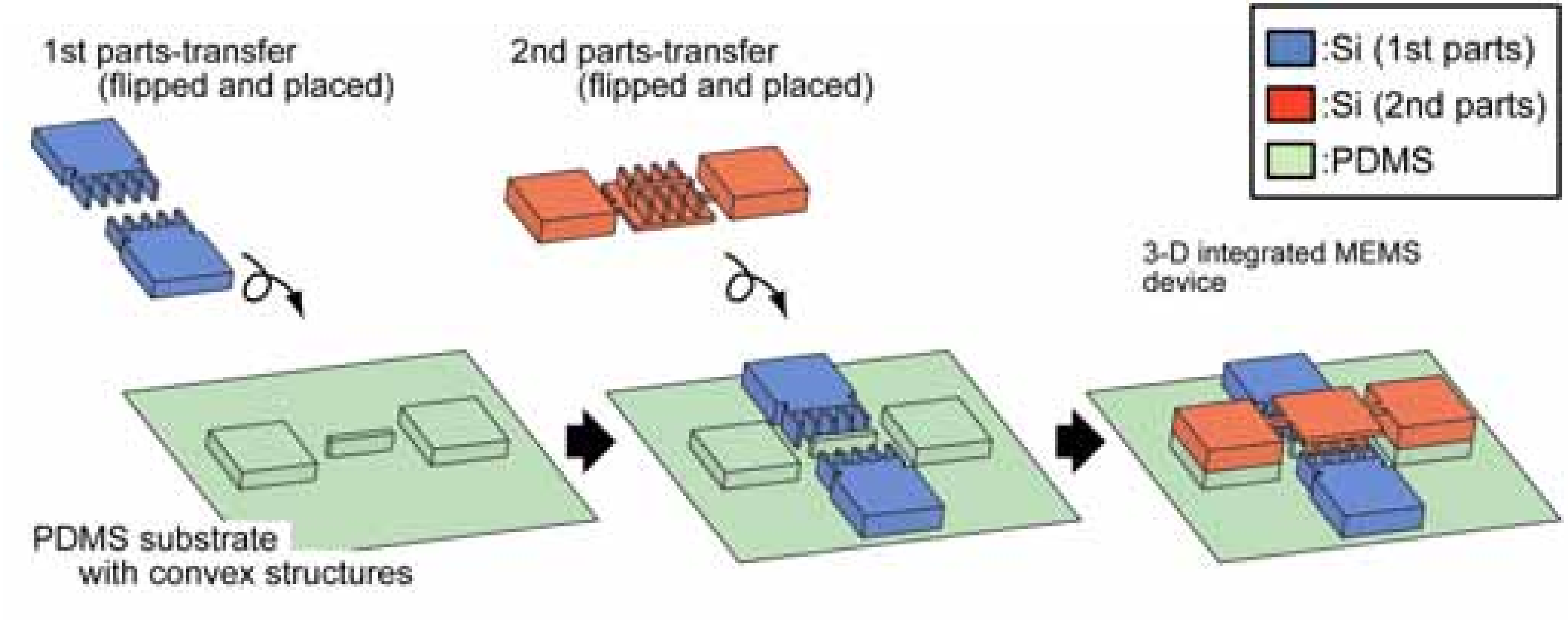
Wire part
- High stretchability
- Using metal (for high conductivity)
- Self-healing function

2. Self-healing metal wire

Small deformation region
Large deformation region

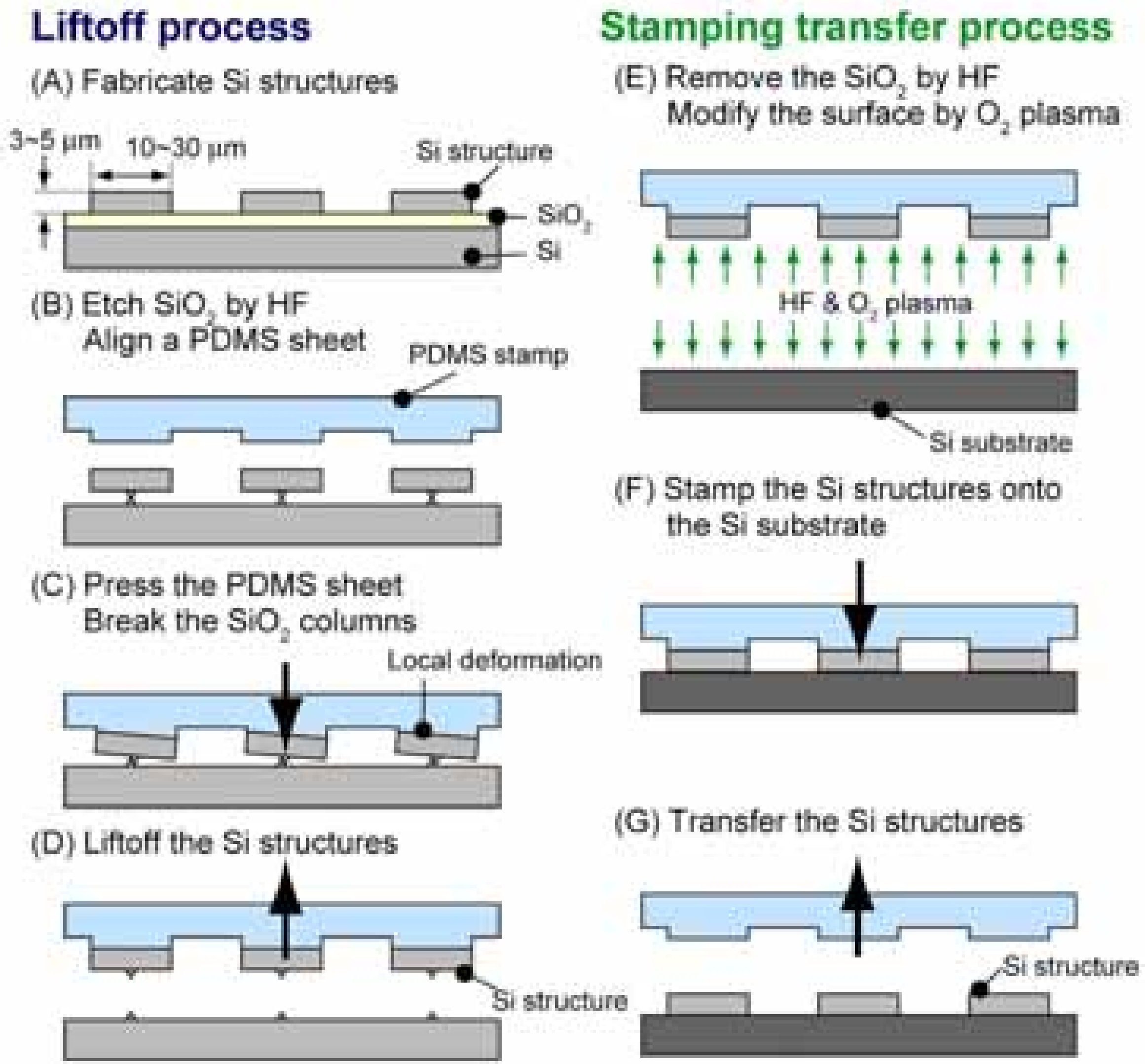
Stamping transfer method

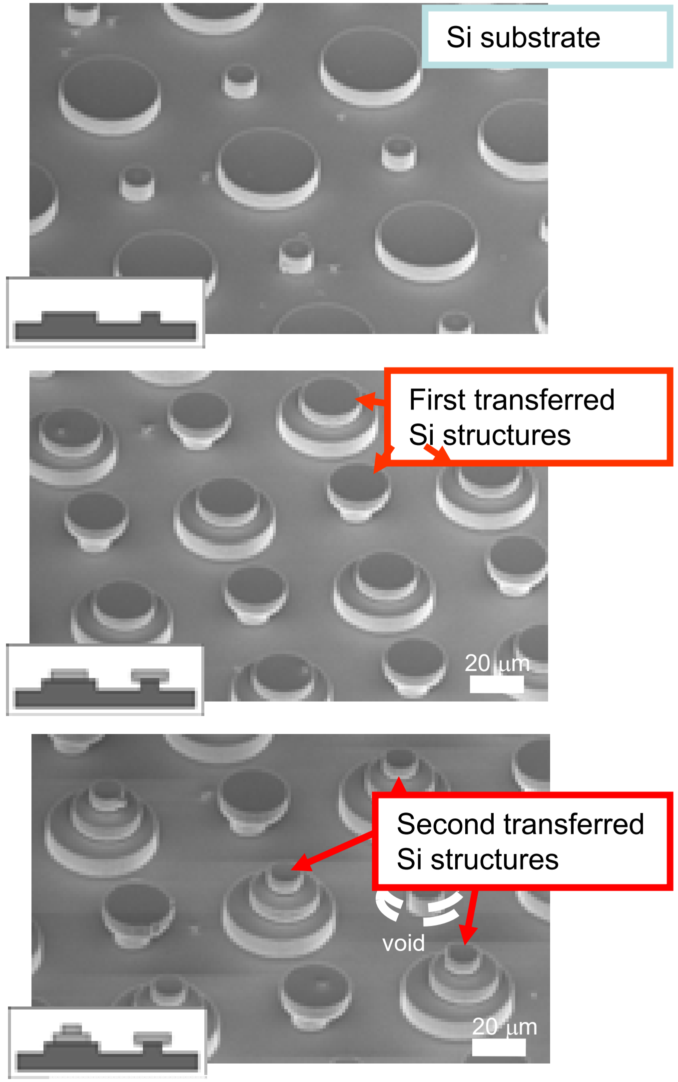
- Transfer silicon parts of sensors or actuators directly onto flexible substrate



  - Enable to fabricate Si-MEMS devices on a flexible substrate
  - Enable to transfer multiple parts (ex. thermoelectric generators, piezoresistive sensors, electrostatic actuators, optical photodiodes)
  - Build three-dimensional structures

Stamping transfer method

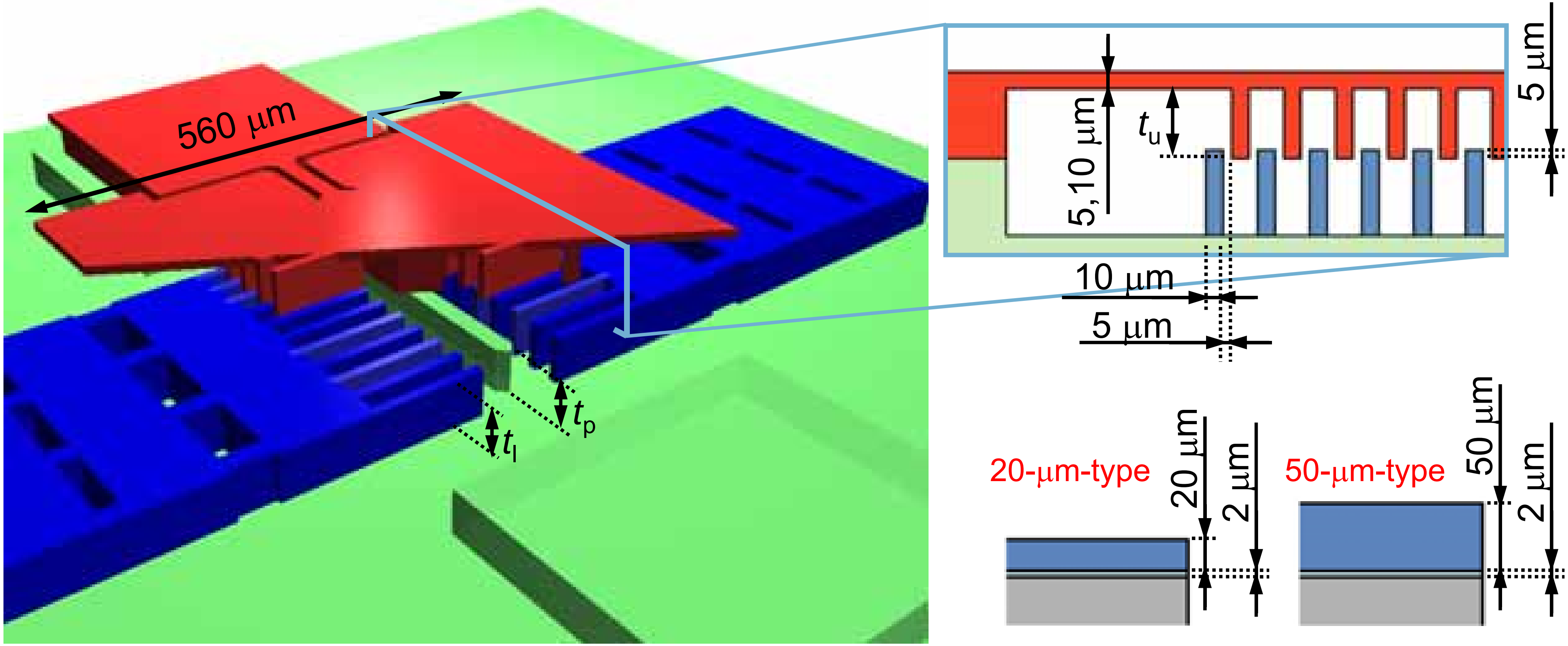




H. Onoe, E. Iwase, *et al.*, *J. Micromech. Microeng.* (2007)

Transfer yield > 80%, Positioning error < ±2 μm

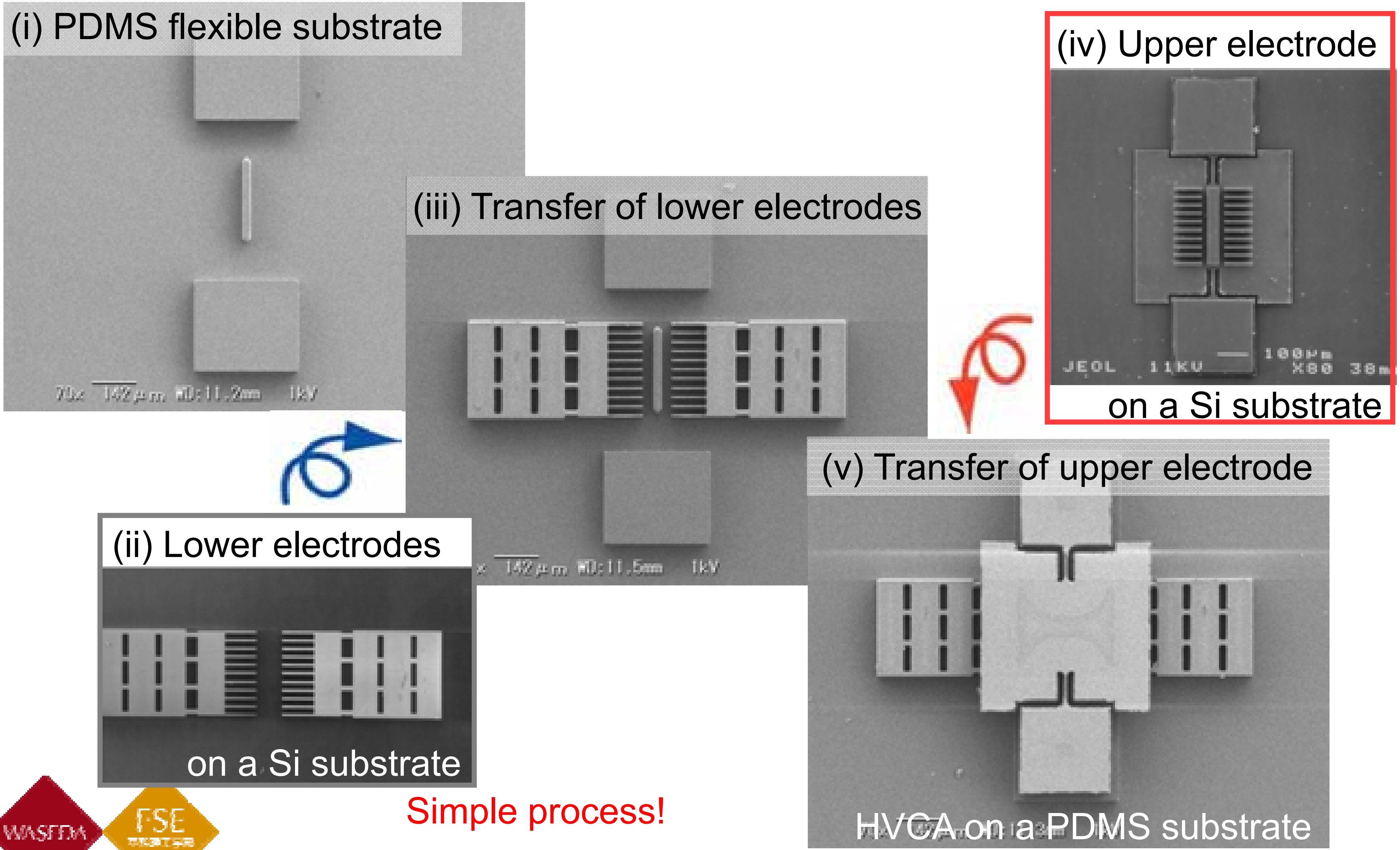
Design of micro scanning mirror



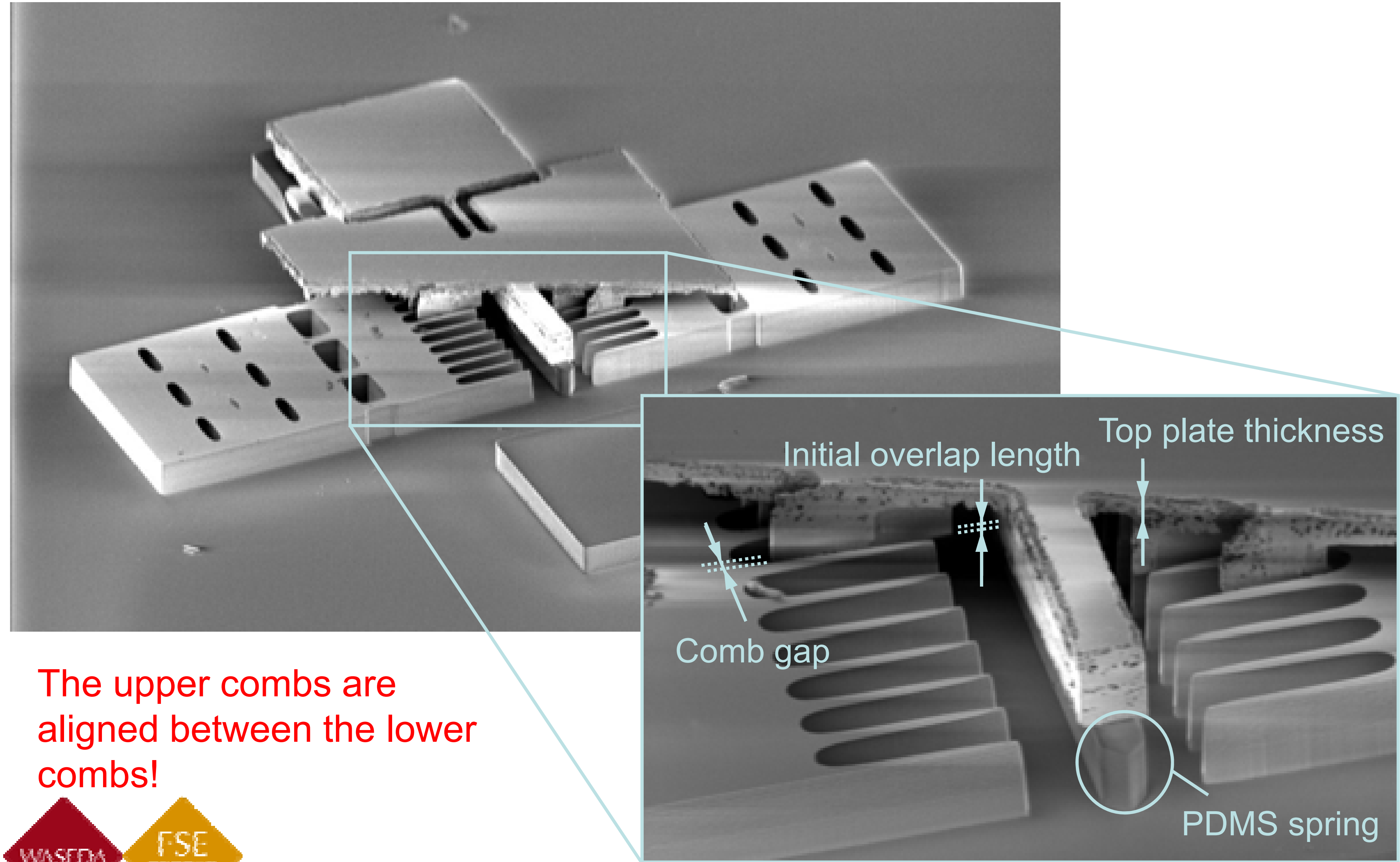
:Si (1st parts)
:Si (2nd parts)
:PDMS

	20-μm-type	50-μm-type
lower electrodes thickness (t_l)	20 μm	50 μm
hidden electrodes thickness (t_u)	15 μm	40 μm
hidden PDMS spring height (t_s)	15 μm	45 μm
maximun tilt angle (θ_{max})	5.74 °	15.5 °

Fabrication process

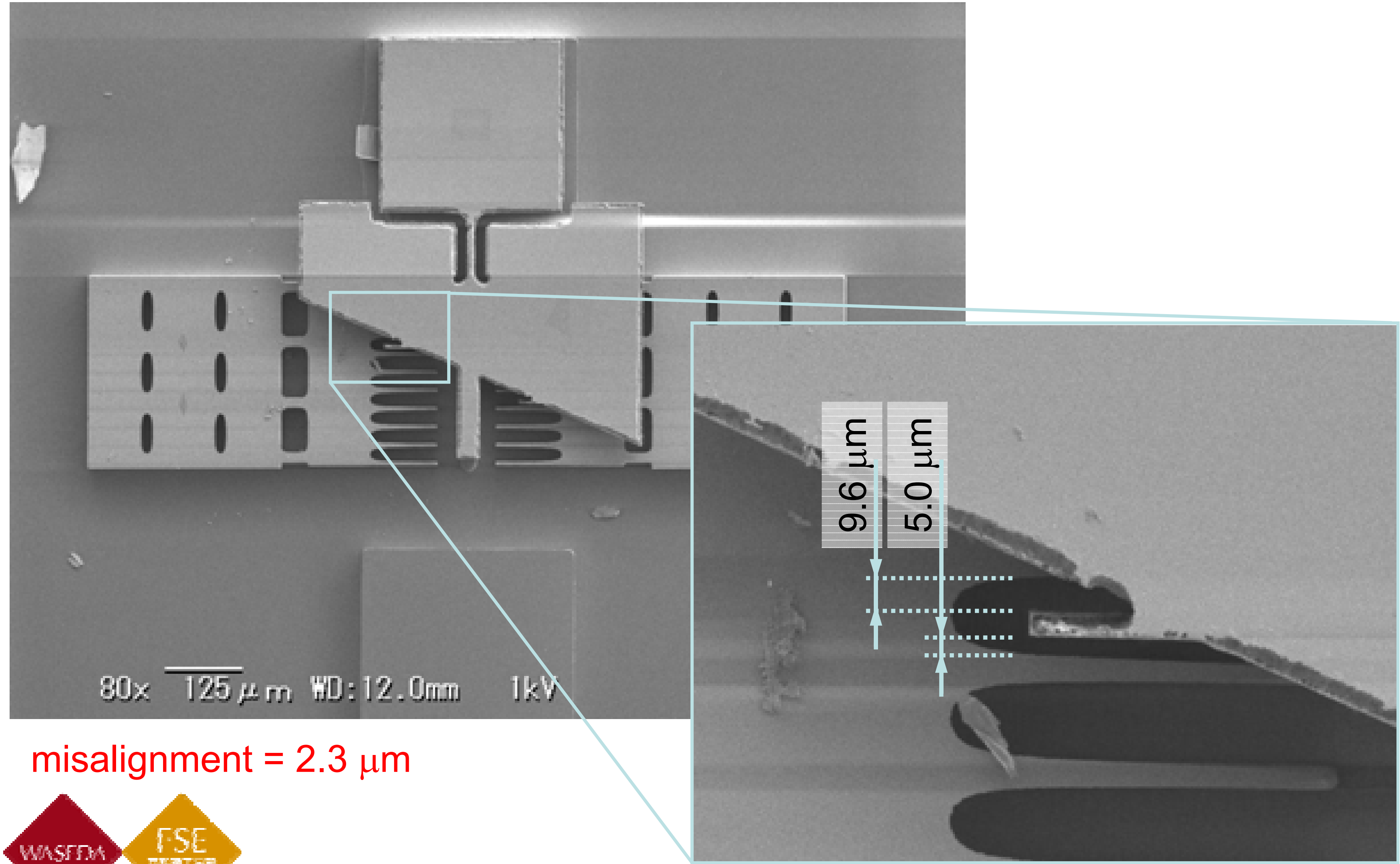


Cut model of micro scanning mirror



The upper combs are aligned between the lower combs!

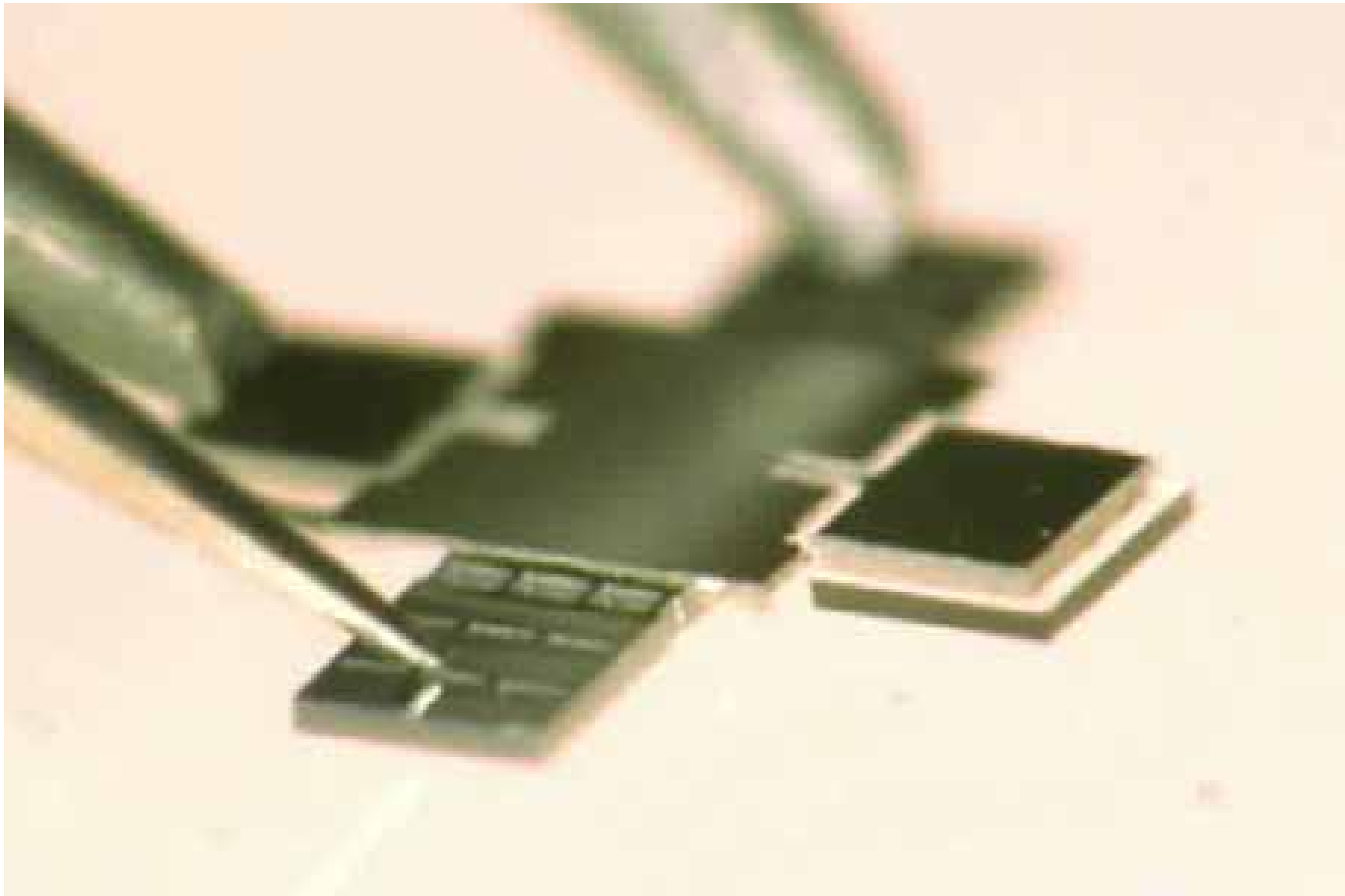
Cut model of micro scanning mirror



misalignment = 2.3 µm

Actuation of micro scanning mirror

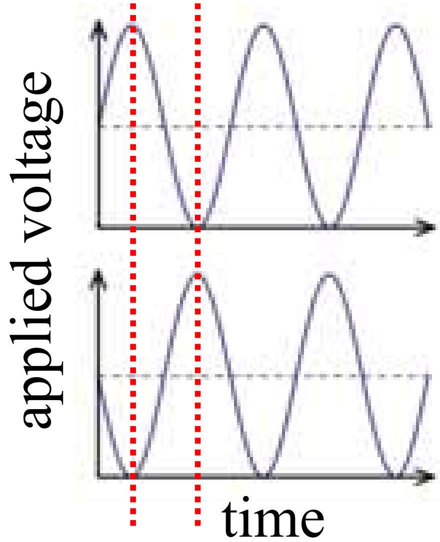
50-μm-type, V = 300 V, f = 1 - 8 Hz

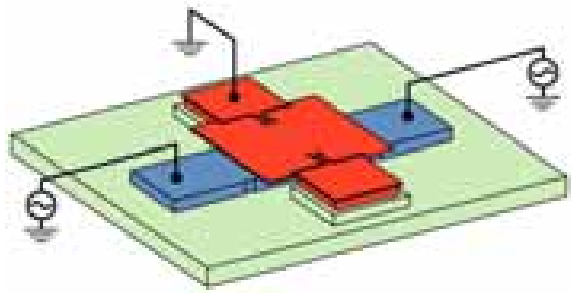


V_u= GND

$V_{l1}=V_0/2(1+\sin(2\pi ft))$

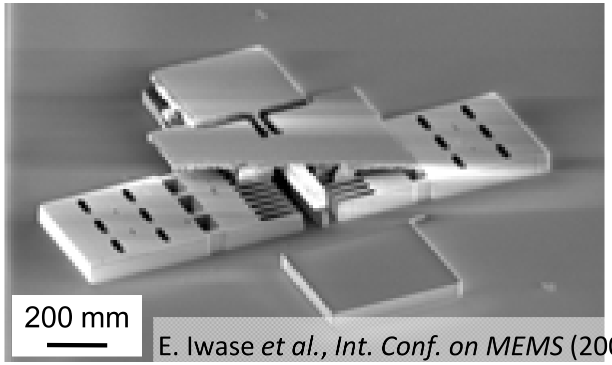
$V_{l2}=V_0/2(1-\sin(2\pi ft))$





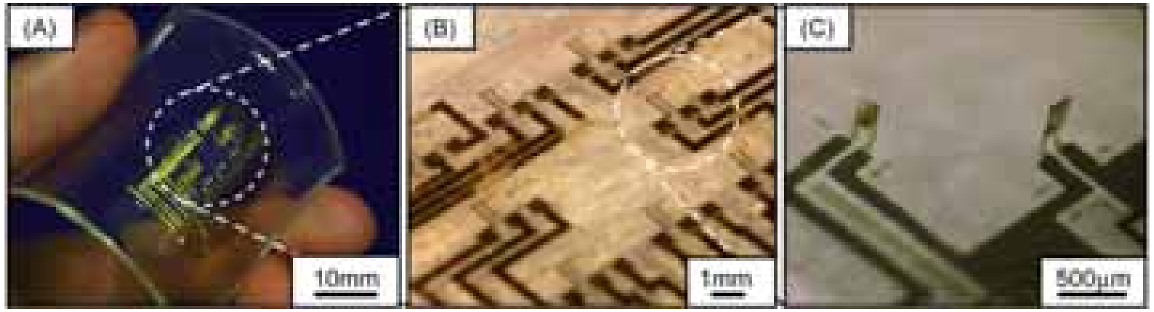
Applications of the stamping transfer method

Complex 3-D Structure & actuator on PDMS



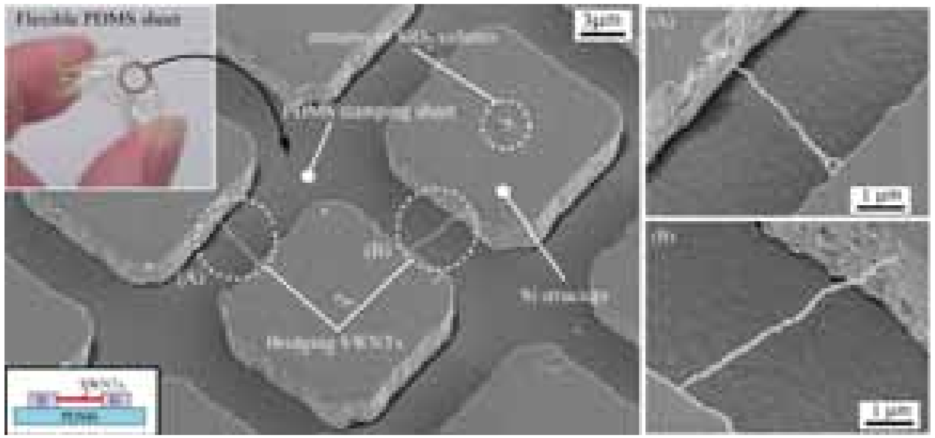
E. Iwase *et al.*, *Int. Conf. on MEMS* (2008)

Flexible Si-based Force Sensor



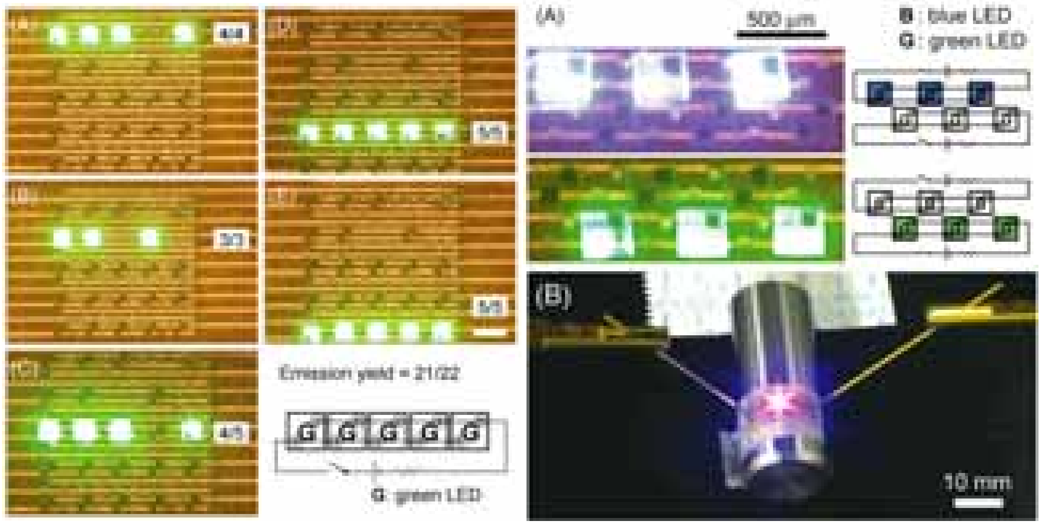
K. Noda, H. Onoe, E. Iwase, *et al.*, *J. Micromech. Microeng.* (2013)

Si block with CNT



Y. Taki, E. Iwase, *et al.*, *Int. Conf. on MEMS* (2009)

Flexible LED display



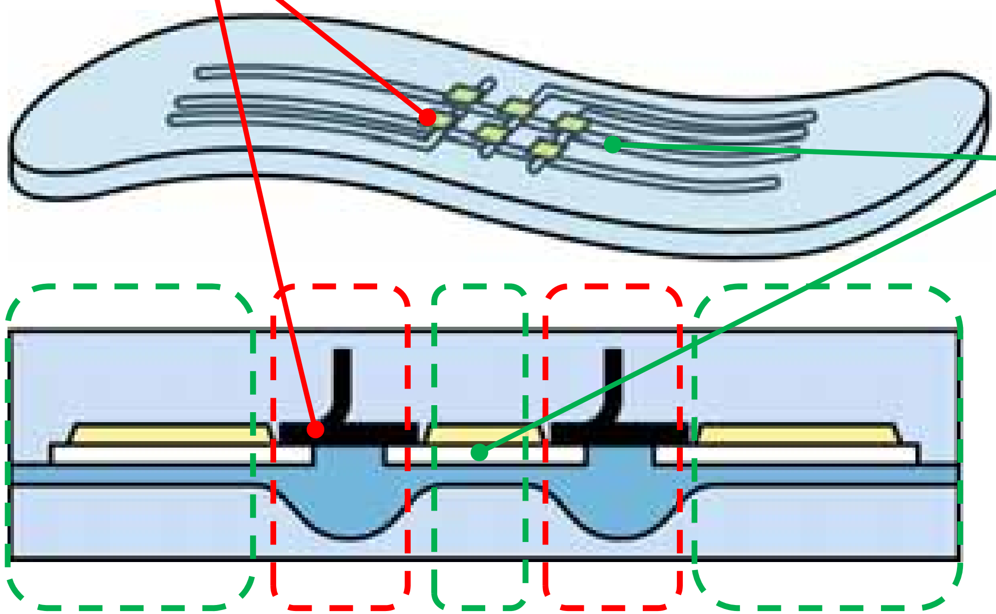
H. Onoe, A. Nakai, E. Iwase, *et al.*, *J. Micromech. Microeng.* (2009)

Challenge: Approach for stretchable device

Rigid & high performance device + Stretchable wire

Functional part
- Using MEMS devices or bare chip (for high performance or sensitivity)
- No deformation

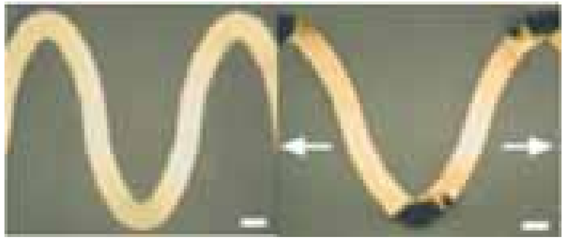
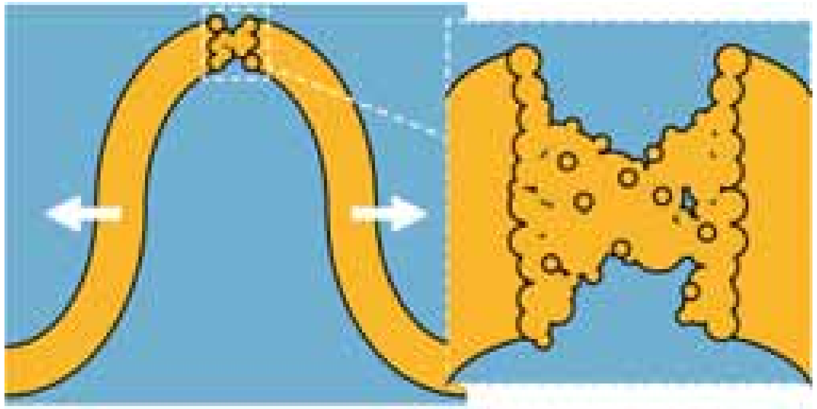
1. Stamping transfer method



Wire part
- High stretchability
- Using metal (for high conductivity)
- Self-healing function

2. Self-healing metal wire

Previous studies of flexible wire

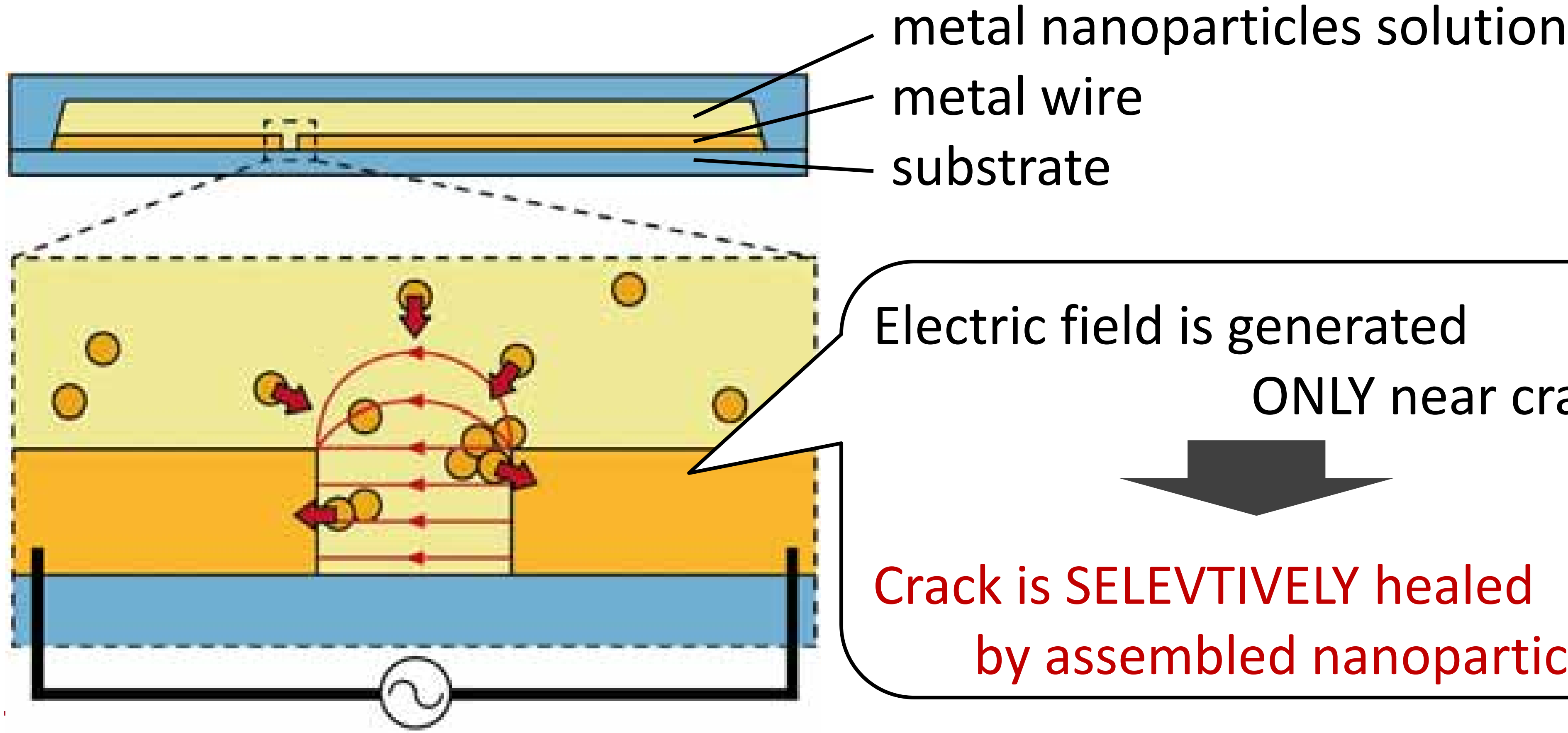
Flexible Wire	Conductivity	Flexibility
Material Conductive Elastomer Wire[1] 	✗ ~10^4 S/m	✓
Shape Curved Metal Wire[2] 	✓ 10^7 S/m	△ cracking
Function  **Curved Metal Wire + Self-Healing**	‖ ✓ ~10^7 S/m	⬇ ✓ **Crack Healing**

1. T. Sekitani *et al.*, *Nature Materials* (2009)   2. D. S. Gray *et al.*, *Adv. Mater.* (2004)

Self-healing metal wire

Providing self-healing function to metal wire

➡ Electric field trapping of gold nanoparticles



Electric field is generated ONLY near crack

Crack is SELEVTIVELY healed by assembled nanoparticles

Analysis of Electric Field Trapping

Total force acting on nanoparticle near crack
(in the case of high frequency voltage)

$$F_{\mathrm{Total}} = F_{\mathrm{VDW}} + F_{\mathrm{ESR}} + F_{\mathrm{DEP}}$$

F_{VDW} : Van der Waals force

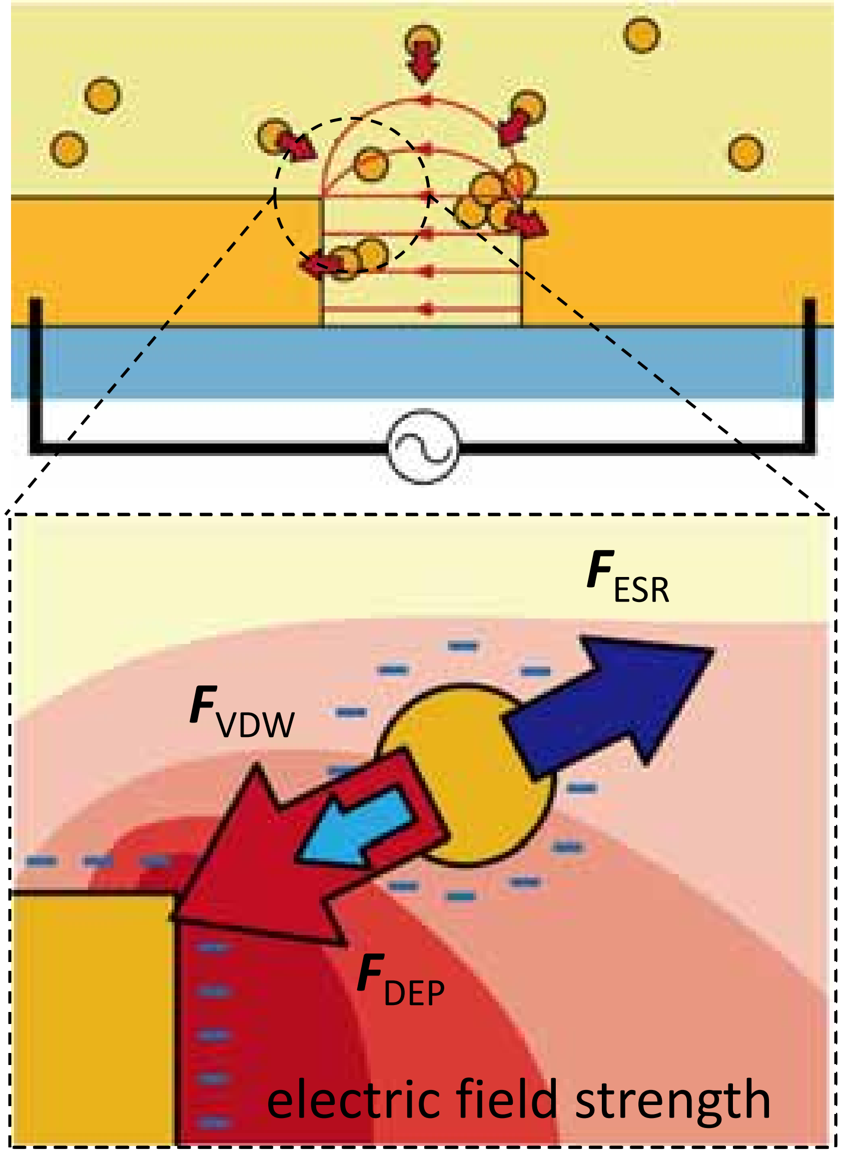
F_{ESR} : Electrostatic repulsive force

determined by solution and particle

F_{DEP} : Dielectrophoresis force

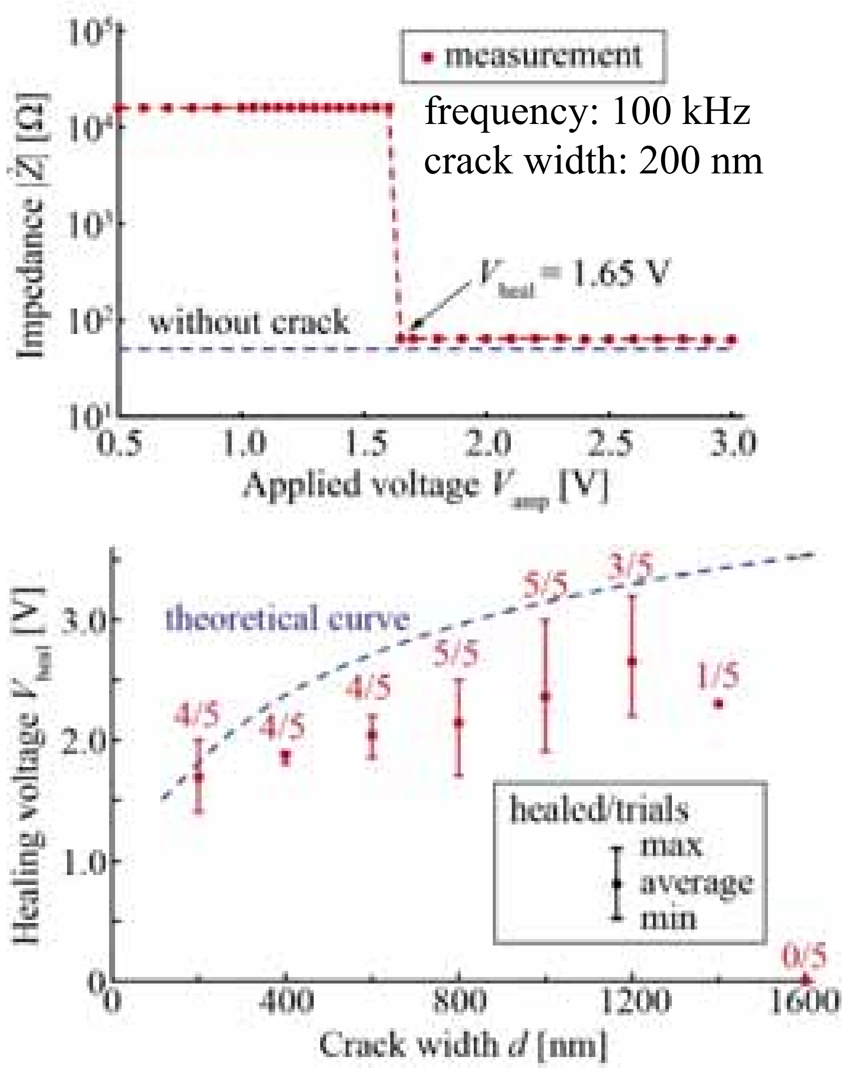
$$\langle F_{\mathrm{DEP}} \rangle = 2\pi\varepsilon_1 r^3 \,\mathrm{Re}[\underline{\mathrm{K}}(\omega)] \nabla E_{\mathrm{rms}}^2$$

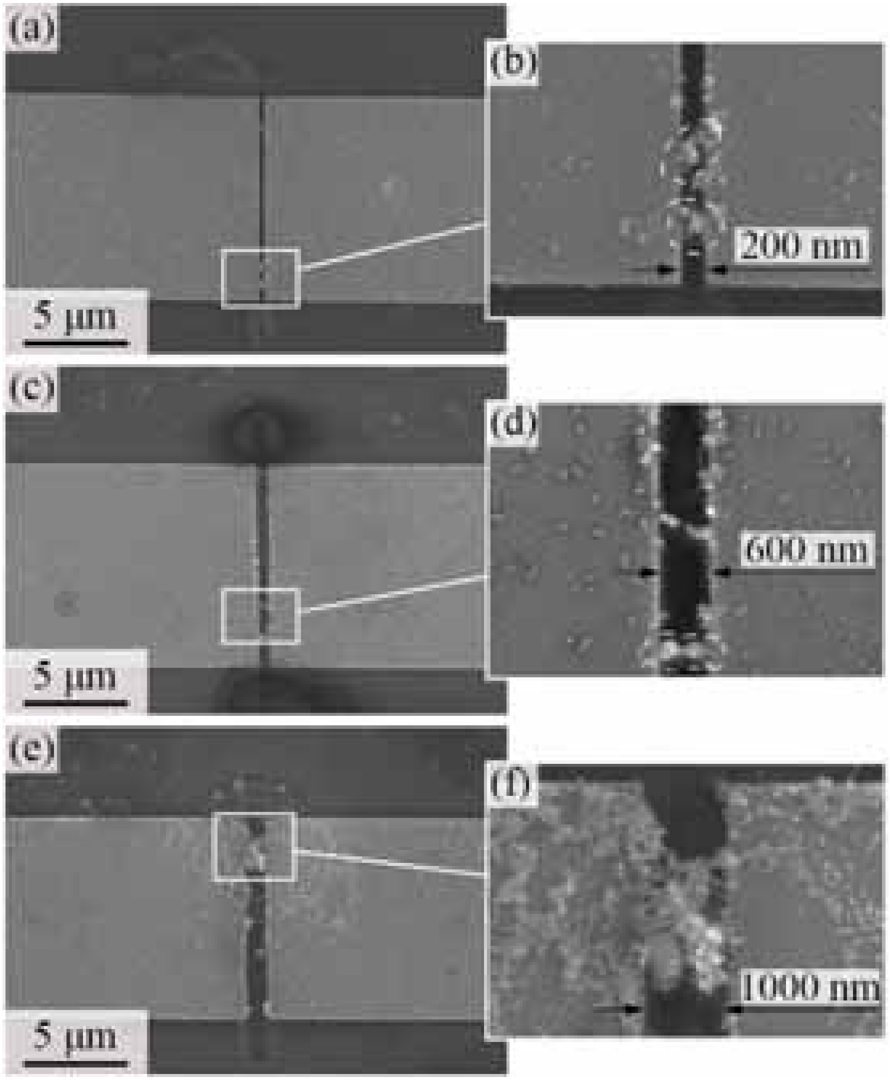
determined by applied voltage



F_{Total} gets attractive near crack ➡ electric field trapping

Self-healing on glass substrate

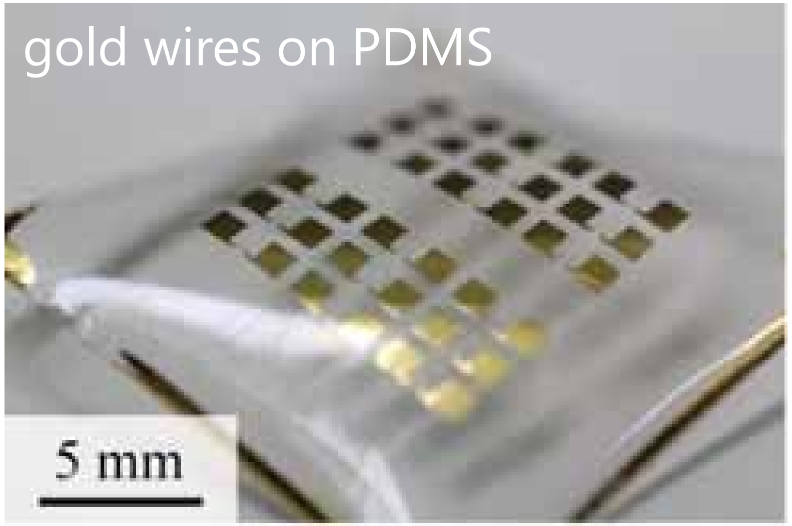


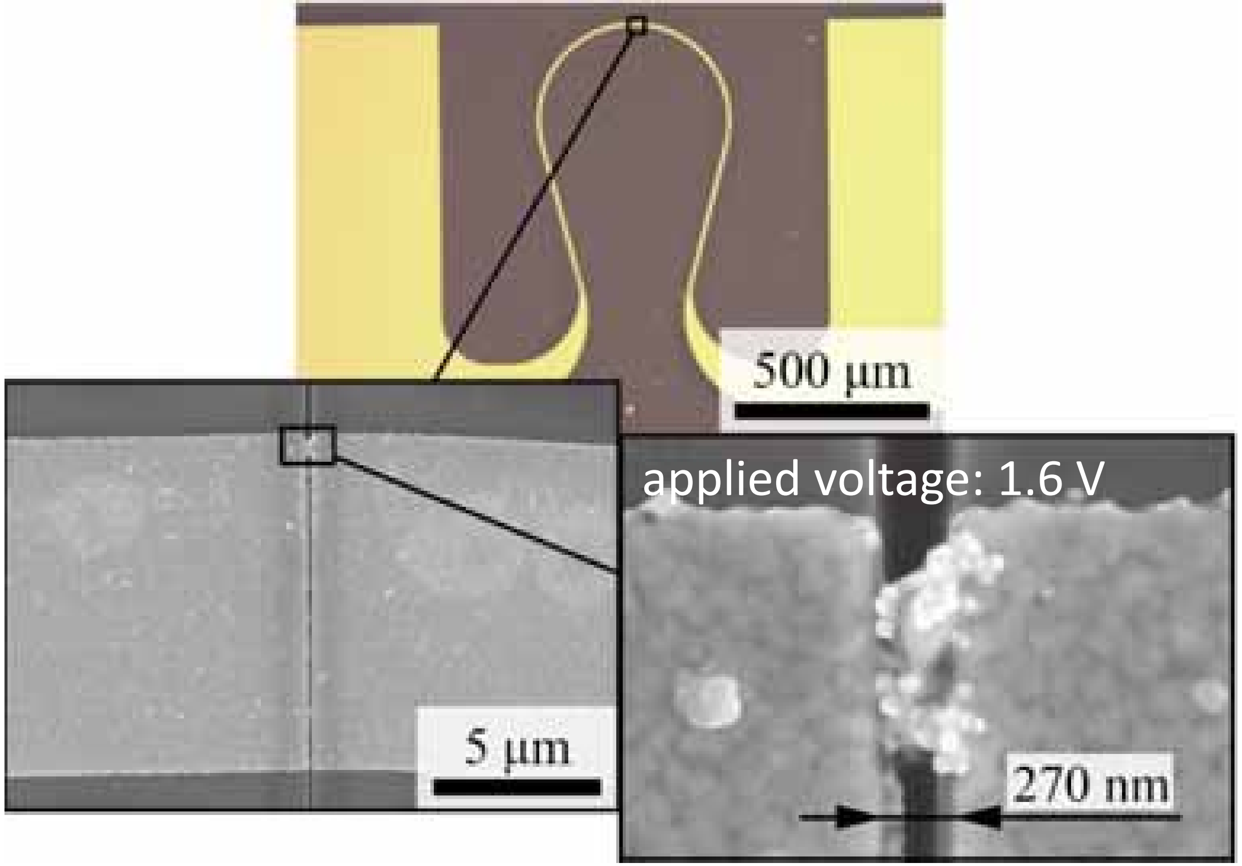


T. Koshi, E. Iwase, *Jpn. J. Appl. Phys* (2015)

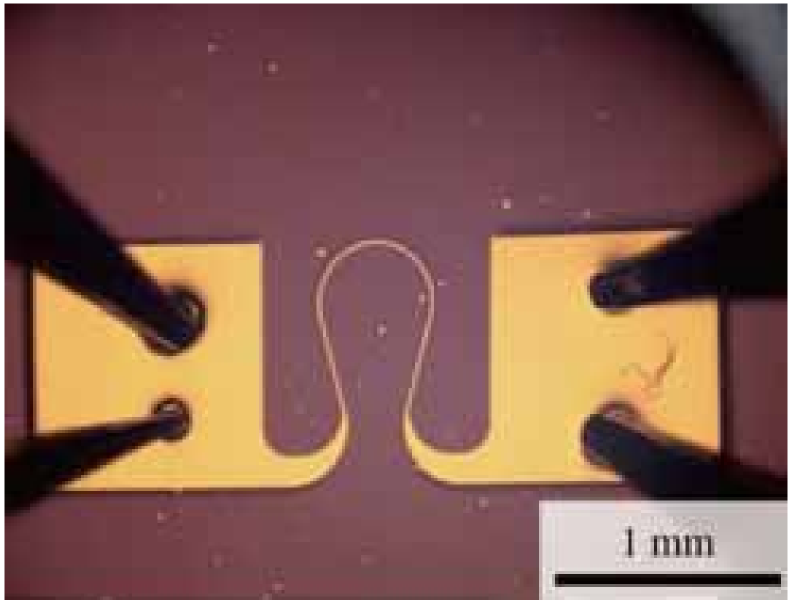
Impedance dropped from 10^4 Ω to 10^1 Ω ➡ Self-healing

Self-healing on Stretchable Substrate





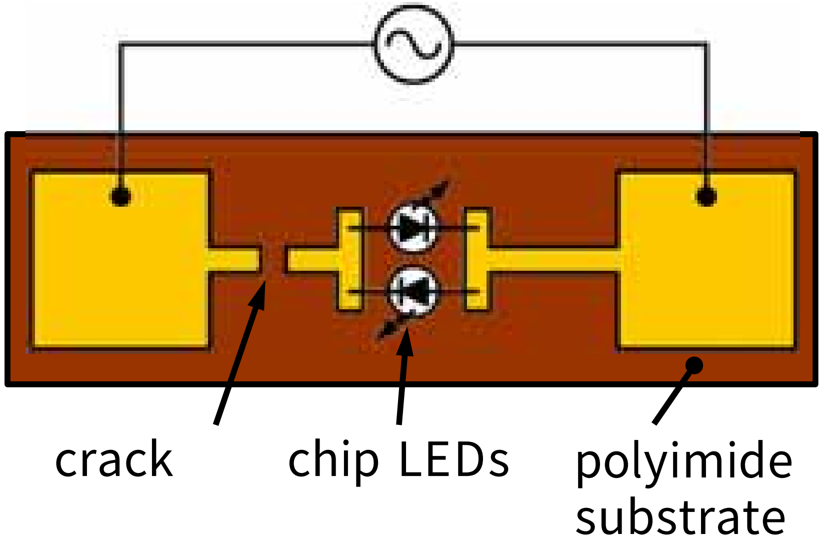
T. Koshi, E. Iwase, *Jpn. J. Appl. Phys* (2015)

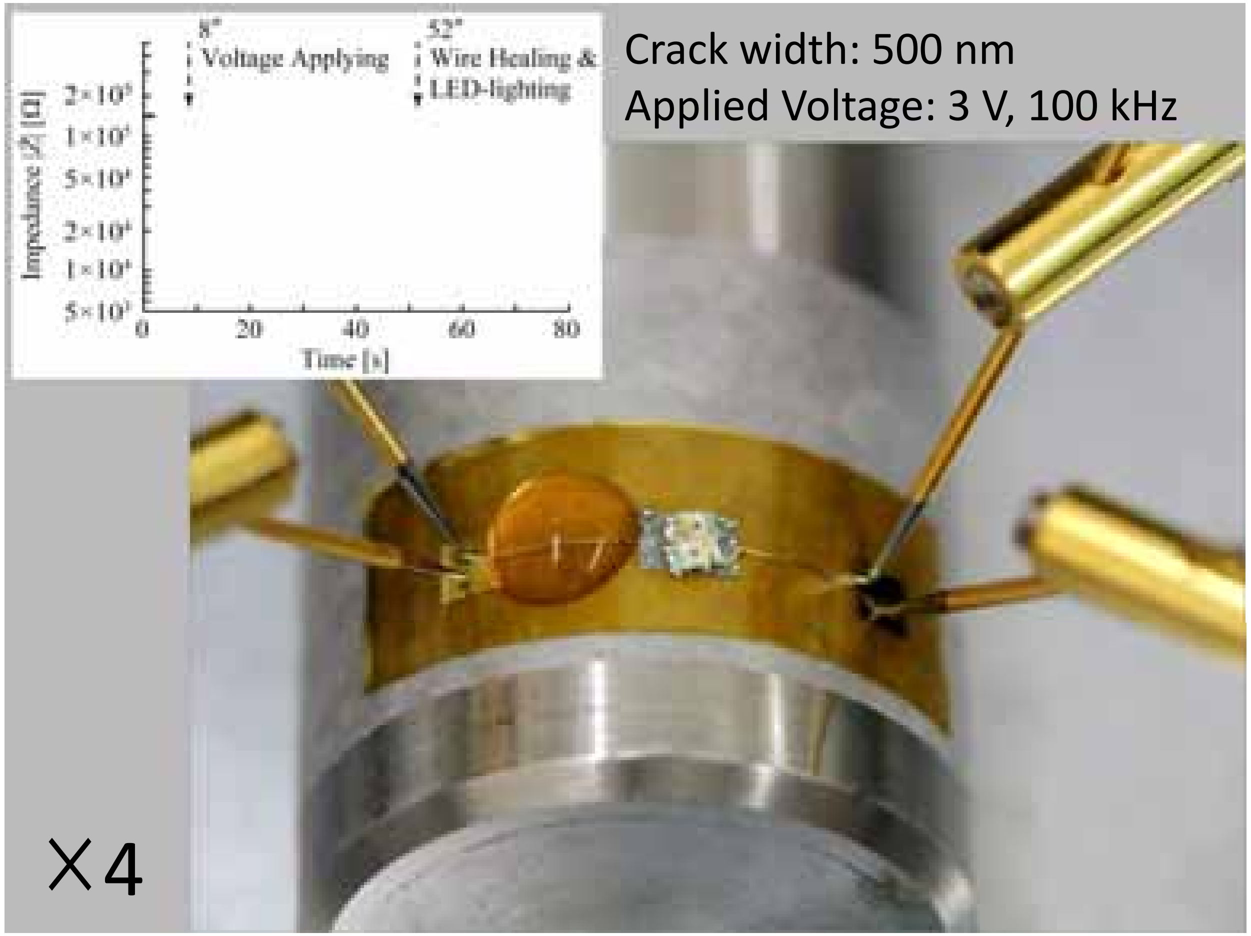


Showing usefulness of self-healing for flexible devices

Device application

Flexible LED device on a curved surface（*r* = 12.7 mm）

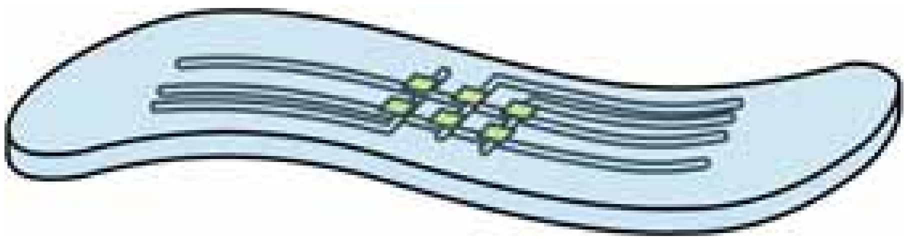


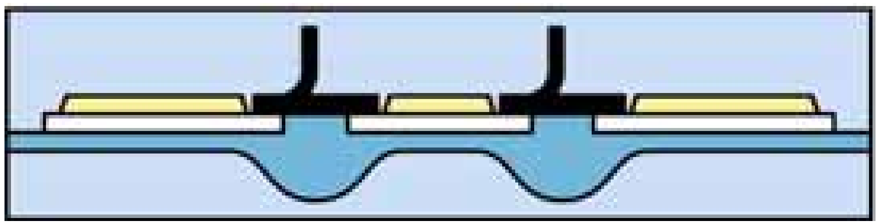


Wire is healed and LEDs are emitted.

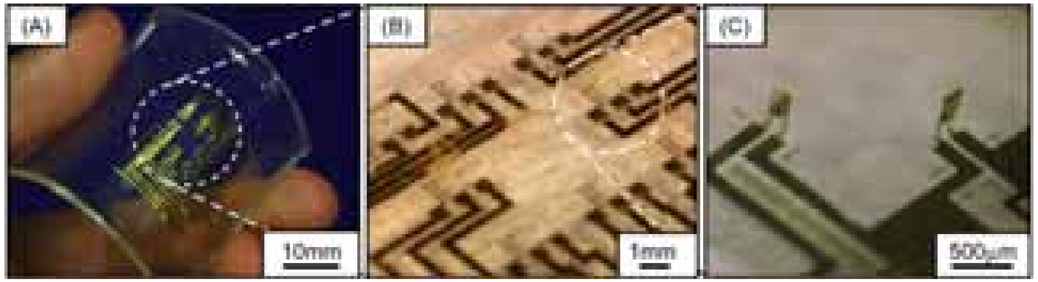
Conclusion

- We proposed a concept of flexible devices using rigid materials to achieve both high performance and high stretchability.





1. Stamping transfer method



2. Self-healing metal wire