MEMS Engineer Forum 2014

Piezoelectric Thin Films and their Applications

April 25, 2014

Eiji Fujii

Advanced Technology Research Laboratories

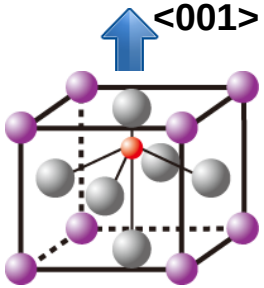
Panasonic Corporation

Table of Contents

Panasonic R&D on Pb-based Ferroelectric Films

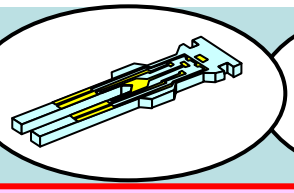
Pb-based Perovskite

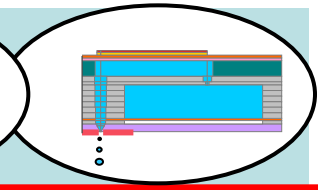
- Ferroelectricity
- Nonlinear optical property
- Pyroelectricity
- Piezoelectricity
- Dielectricity



Devices & Applications

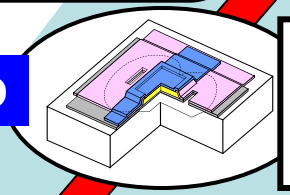
PZT / Si





’08 Actuators for IJ heads (800 nozzle)
’06 Angular rate sensors for image stabilization of DSC
’04 Actuators for IJ heads (400 nozzle)
’03 Angular rate sensors for a car navigation system

PLT / MgO



’97 Micro infrared sensors and ear thermometer
’93 Pyroelectric sensors applied to air conditioner

’01 Piezoelectric (001)PZT films on Si substrate

Materials

’96 Piezoelectric (001)PZT films
’87 c-axis oriented PZT films
’85 c-axis oriented PLT films
’83 c-axis oriented $PbTiO_3$ films
’79 Start of study for ferroelectric films

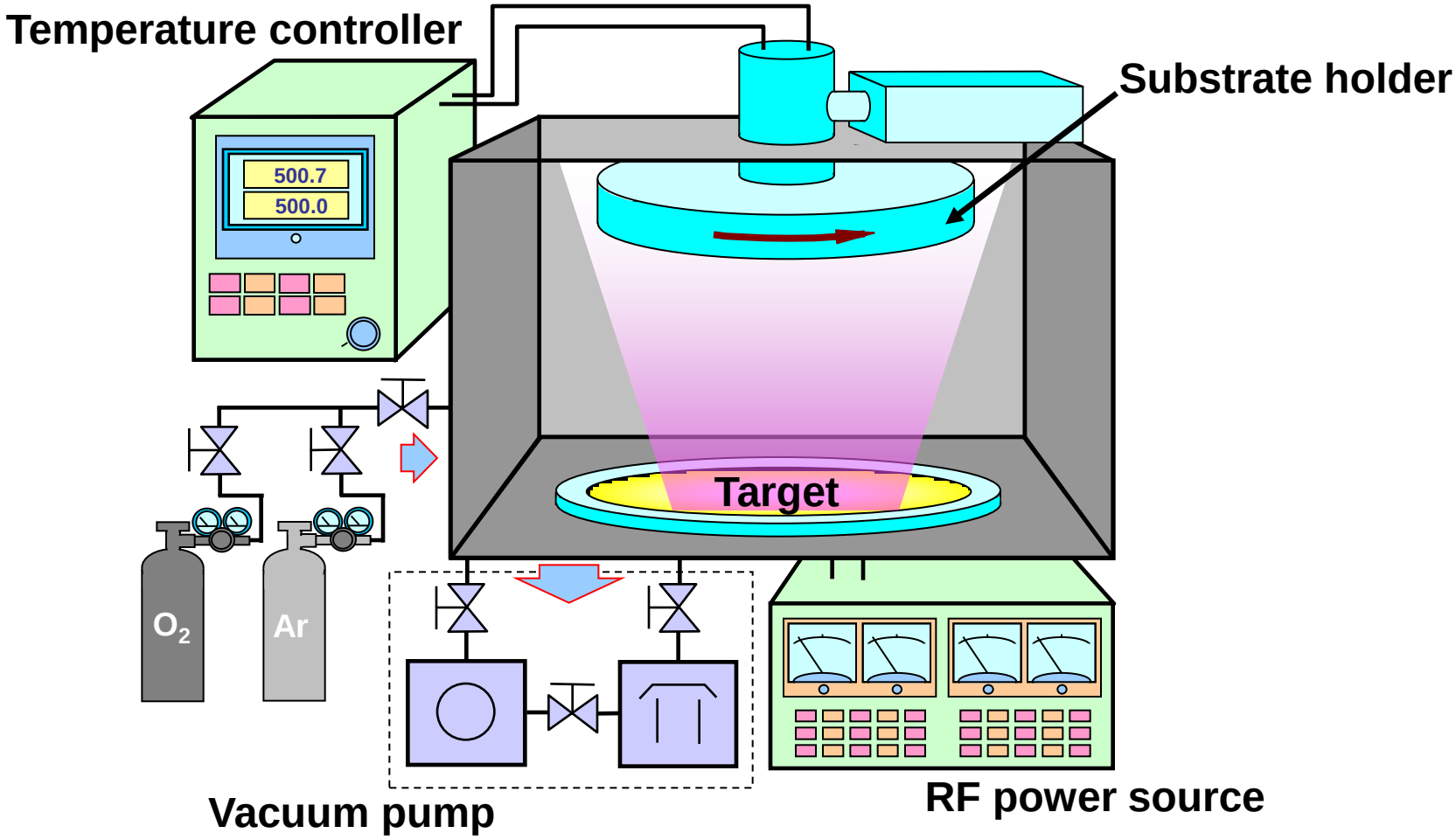
with self-polarization on MgO substrate

80 90 00 03 04 06 08 14

Table of Contents

Preparation of PZT and PMN-PZT Films

RF magnetron sputtering



Preparation of PZT Films

Sputtering conditions

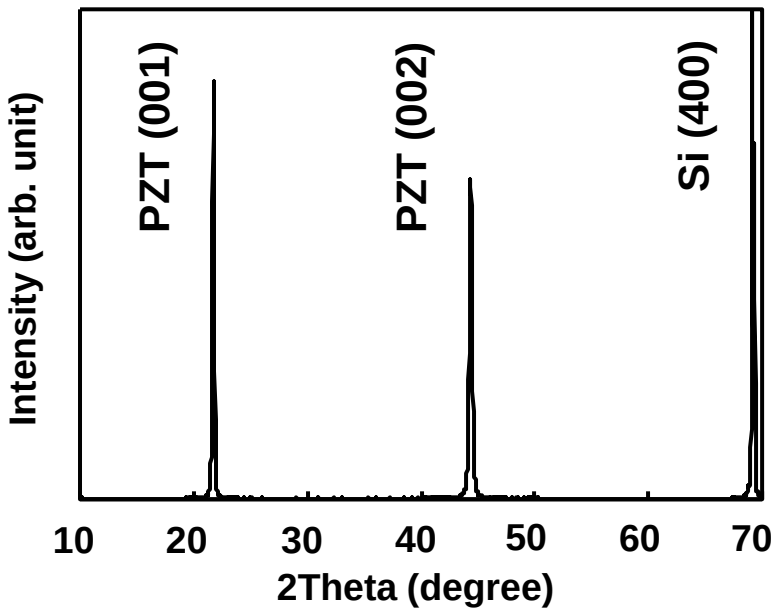
- **Target:** $Pb(Zr_xTi_{1-x})O_3$ + 0.2PbO
  [x=0.5～0.6]
  around morphotropic phase boundary (MPB)
- **Substrate:** Si(100)
- **Temperature:** 500 ~ 650 ˚C
- **RF Power:** ~2 W/cm^2
- **Gas Pressure:** 0.2 ~ 0.5 Pa
- **Deposition Rate:** 10 ~ 100 nm/min
- **Bottom electrode:** (111)Pt, (111)Ir

- **Film Thickness :** 3 μm

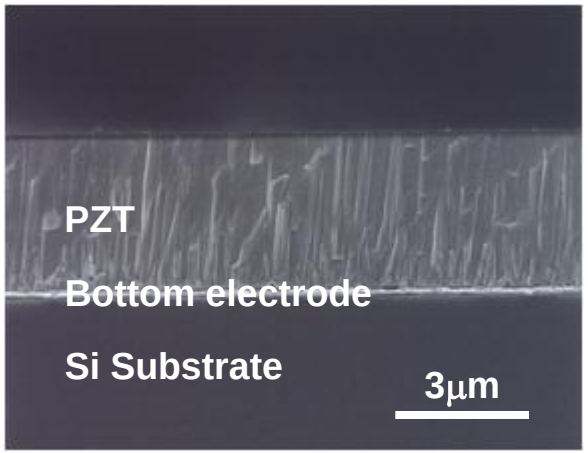
Properties of PZT Films on Si

Zr/Ti = 53/47

XRD pattern



SEM image (cross section)



Measured at 1kHz

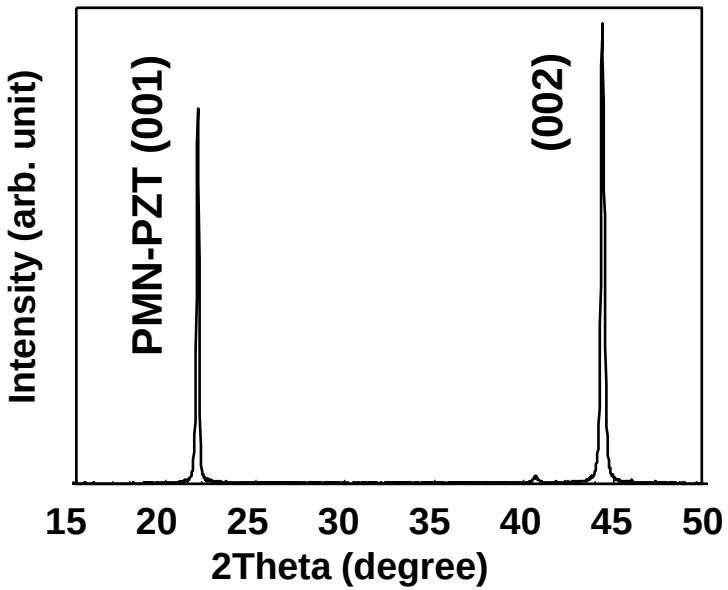
Piezoelectric constant	$-d_{31}$=150 (pm/V) $-e_{31}$=13.9 (C/m^2)
Relative dielectric constant (ε_r)	700
Dielectric loss factor (tanδ)	0.02
Pyroelectric coefficient (γ)	1.3 x 10^{-8} (C/cm^{2}K)

E. Fujii *et al.*, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control 54*, 2431 (2007)

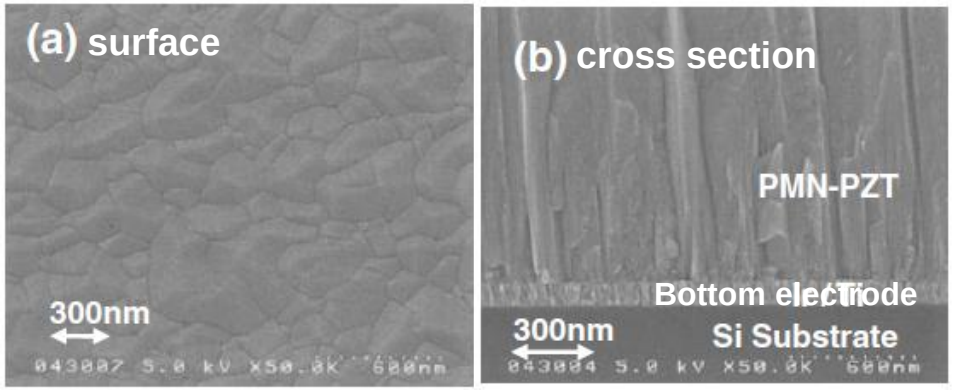
Properties of PMN-PZT Films on Si

0.125PMN–0.875PZT

XRD pattern



SEM images



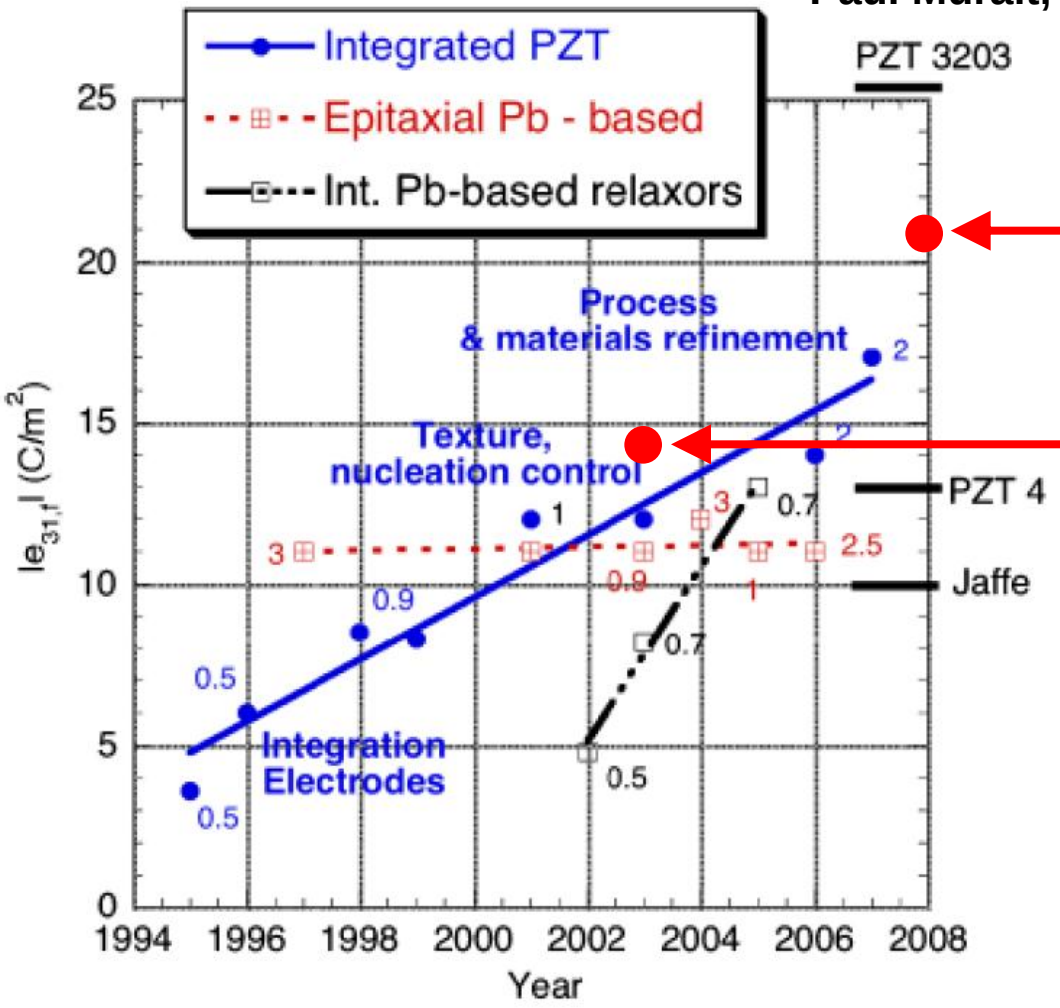
Measured at 1kHz

Piezoelectric constant	$-d_{31}$=225 (pm/V) $-e_{31}$=20.8 (C/m^2)
Relative dielectric constant (ε_r)	1,400
Dielectric loss factor (tanδ)	0.03
Pyroelectric coefficient (γ)	1.9 x 10^{-8} (C/cm^{2}K)

S. Fujii *et al.*, *Jpn. J. Appl. Phys. 48*, 015502 (2009)

Performance of PZT and PMN-PZT Films

"Recent Progress in Materials Issues for Piezoelectric MEMS"
Paul Muralt, *J. Am. Ceram. Soc. 91*, 1385 (2008)



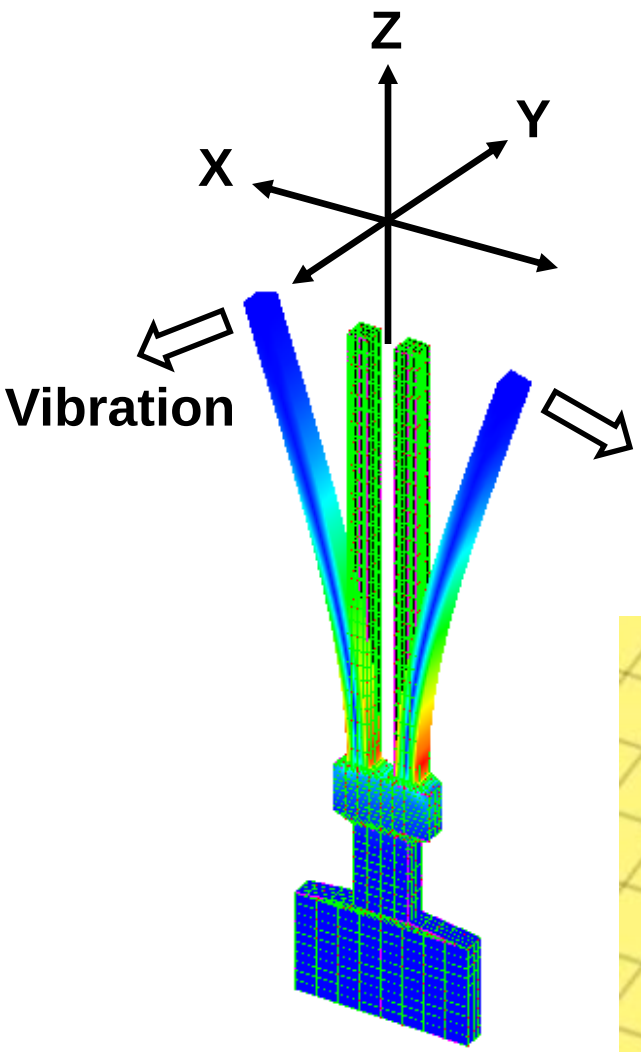
PMN-PZT; 20.8 C/m^2

PZT; 13.9 C/m^2

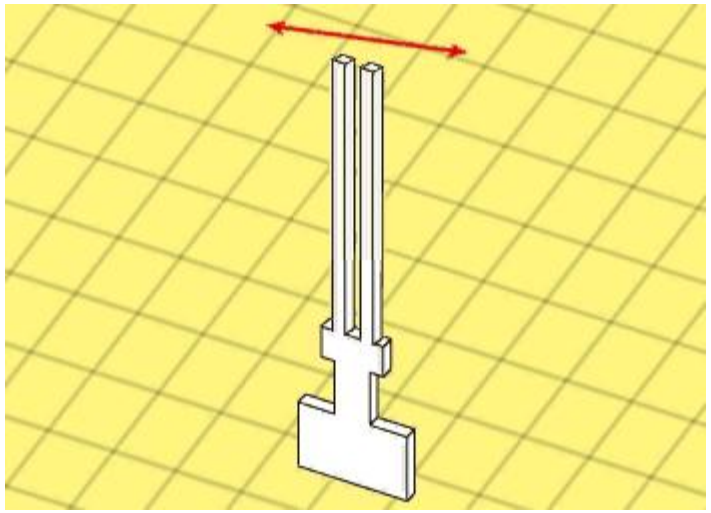
Fig. 2. The history of the transverse piezoelectric coefficient $e_{31,f}$

Table of Contents

Principle of Angular Rate Sensor



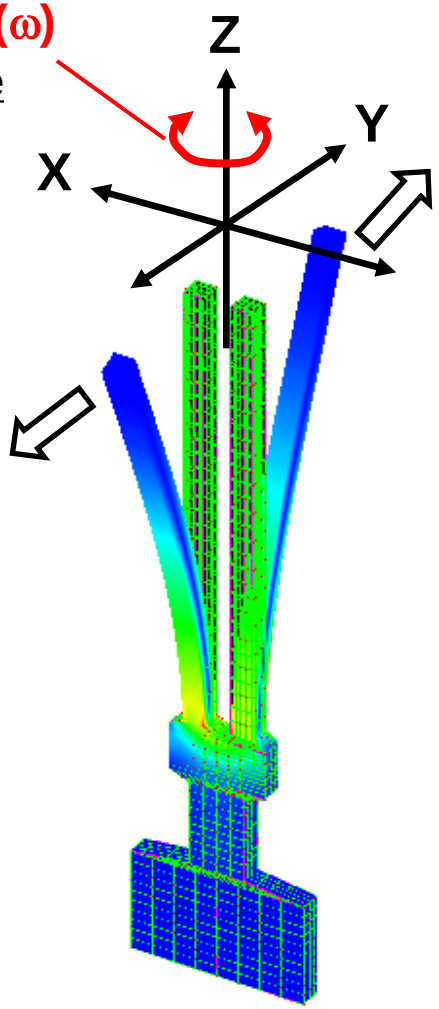
Driving Mode



Angular rate (ω)

Coriolis Force

(Fc=2mVω)

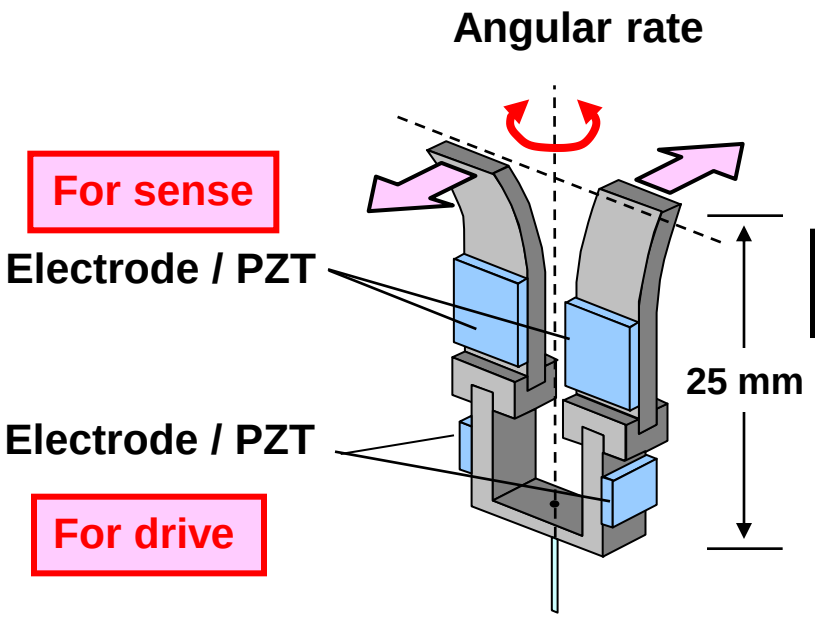


Sensing Mode

Structure of Si Tuning Fork Vibrator

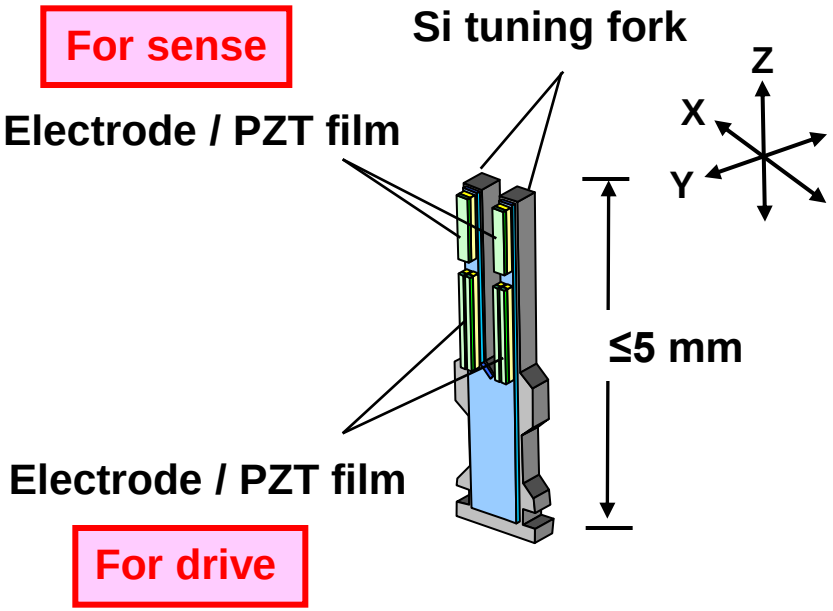
Conventional sensor

◆Piezoelectric materials (bulk PZT); arranged for three dimensions



PZT/Si tuning fork vibrator

◆Piezoelectric materials and Electrodes; arranged on identification plane

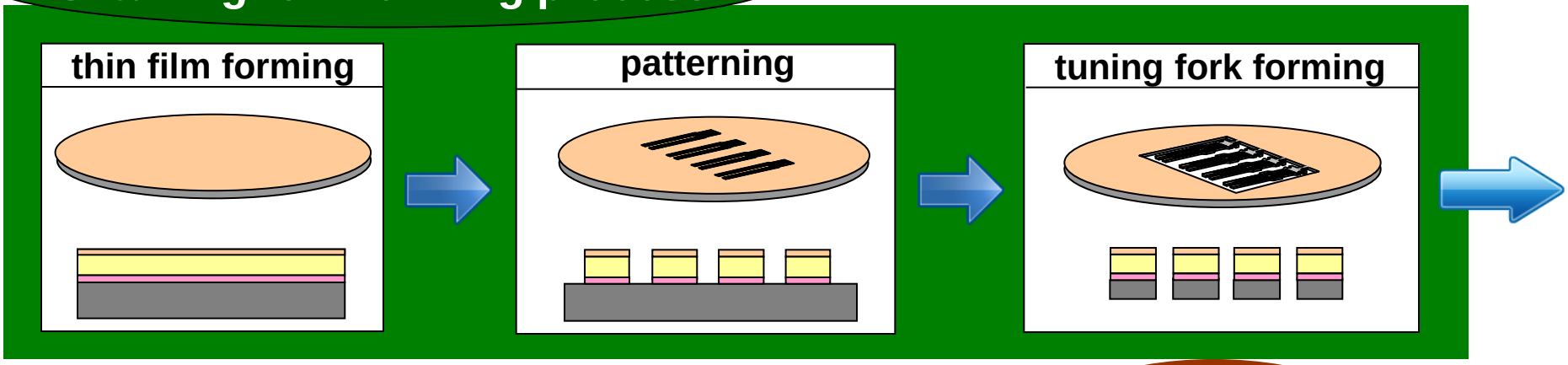


Structure: Complicated
Downsizing: Difficult

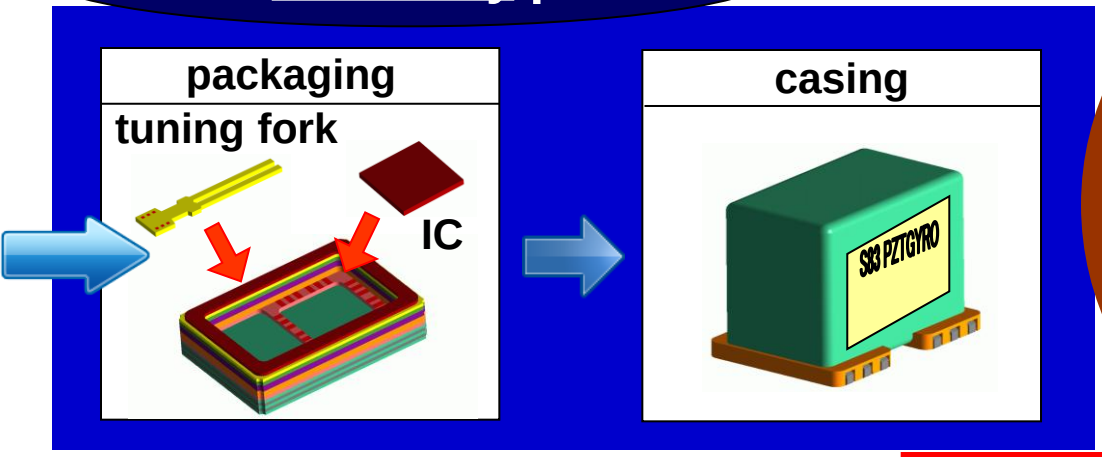
Structure: Simple
Downsizing: Easy

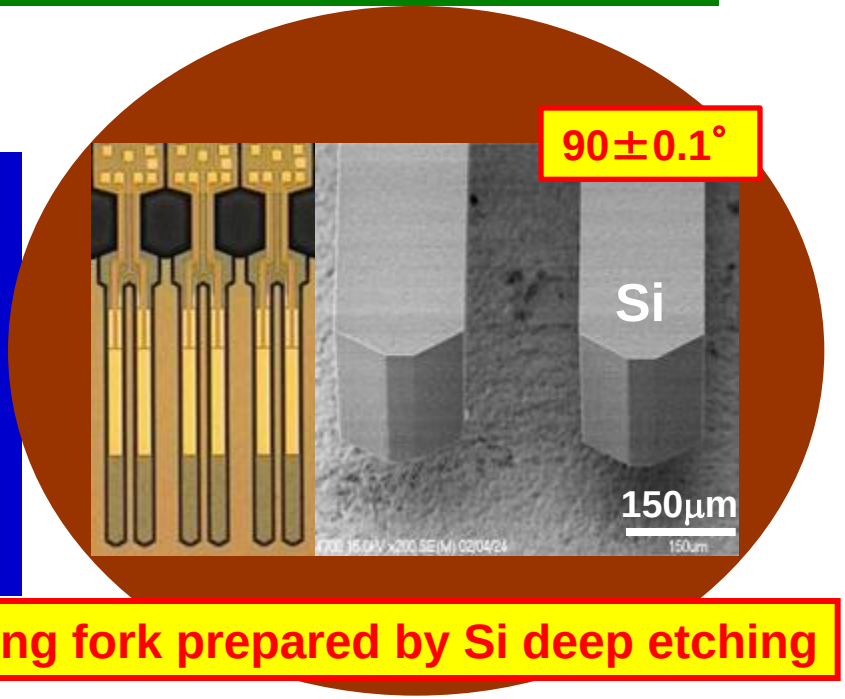
Manufacturing the Angular Rate Sensor

Si tuning fork forming process



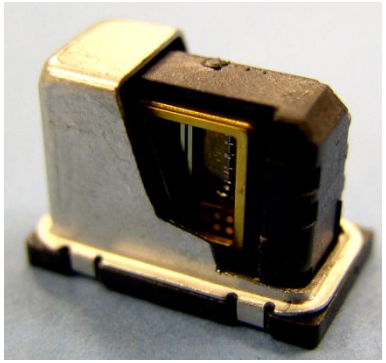
sensor assembly process

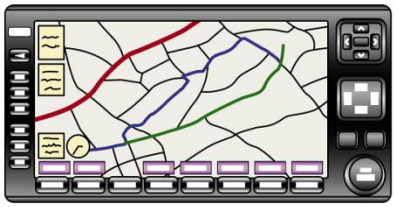


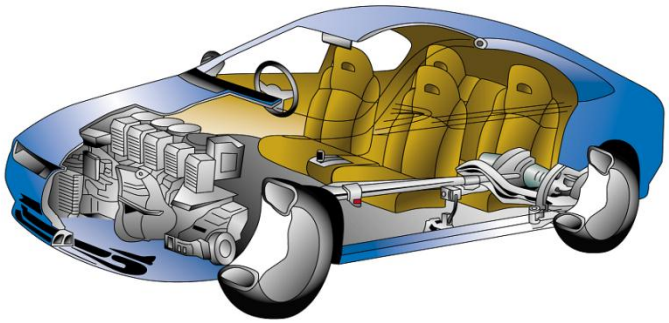


● tuning fork prepared by Si deep etching

Angular Rate Sensor for Car Navigation System

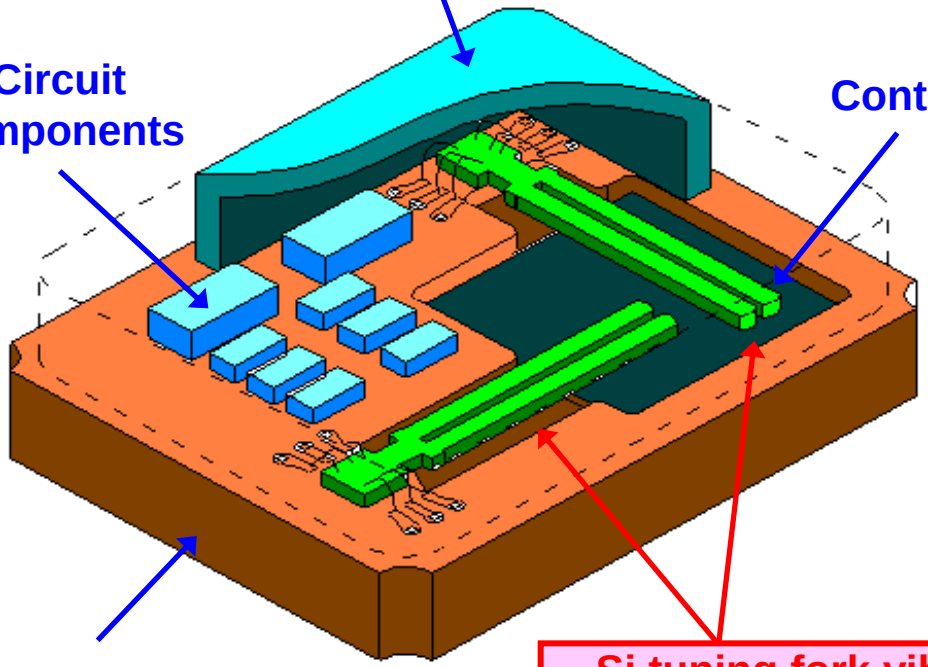






Angular Rate Sensor for DSC

image stabilizing system

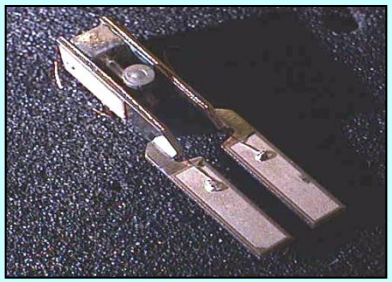


Panasonic Angular Rate Sensors

Metal tuning fork Piezoelectric Bulk

Car Navigation

[1994～]



Volume Ratio 100

Quartz tuning fork

Car Navigation

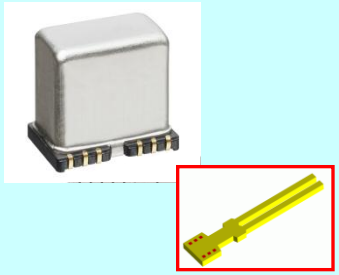
[1999～]

18

PZT/Si tuning fork

Car Navigation

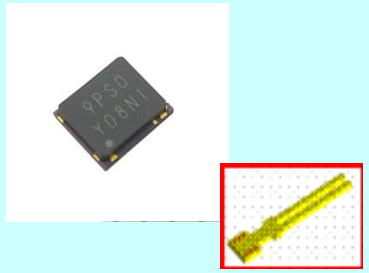
[2003～]



8

DSC

[2006～]



0.2

PZT/Si motion sensor

Smartphone
Gaming hard ware

[2011～]

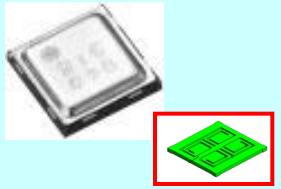
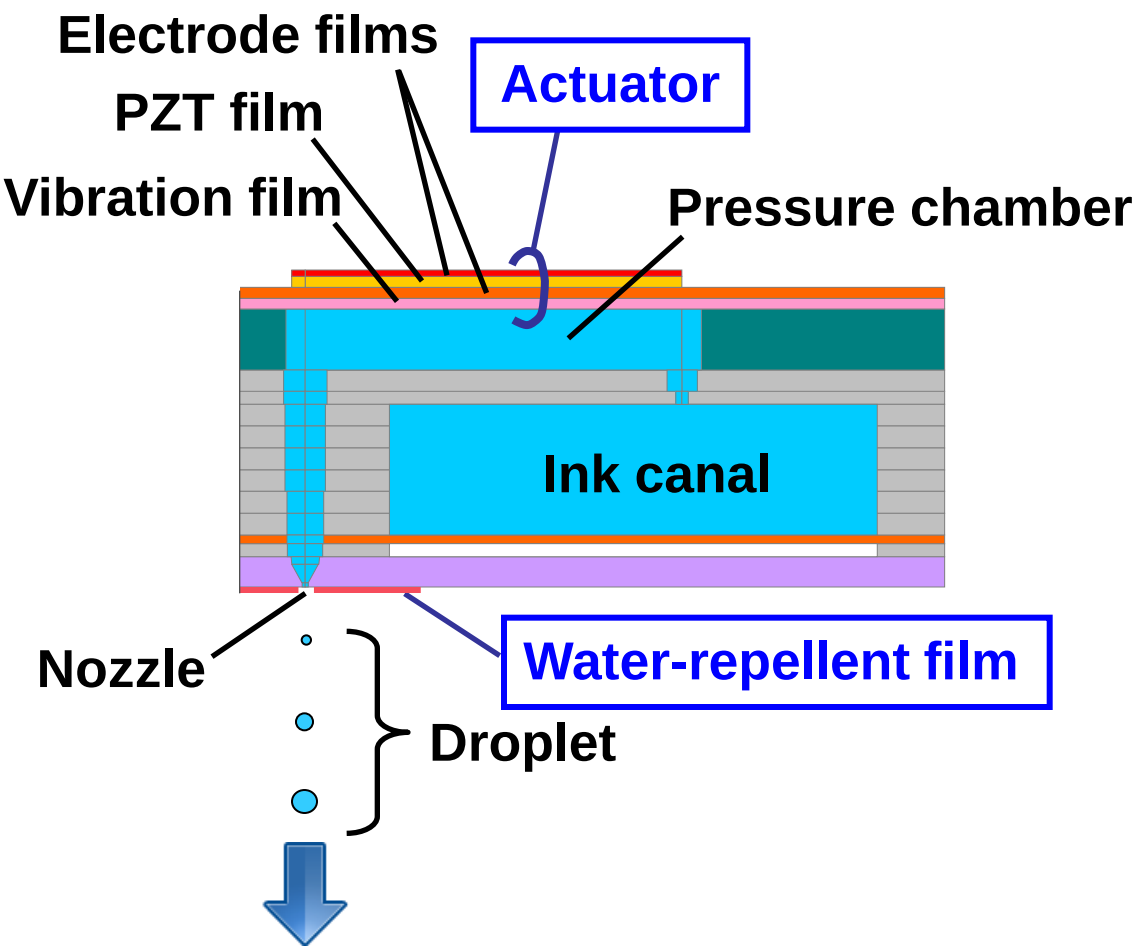
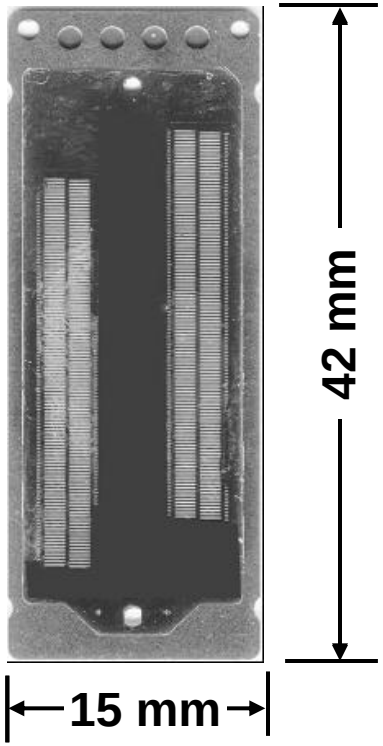


Table of Contents

Structure of Inkjet Head

Cross sectional illustration





400 nozzles

Accurate and stable drop control

Manufacturing the Inkjet Head

《film forming process》

Electrode film

Substrate

PZT film

Vibration film (common electrode)

《actuator element process》

Pressure chamber elements bonding

substrate etching

electrodes patterning

PZT film patterning

Estimation for displacement and resonance frequency

《 head assemble process》

《 nozzle element 》

Nozzle forming

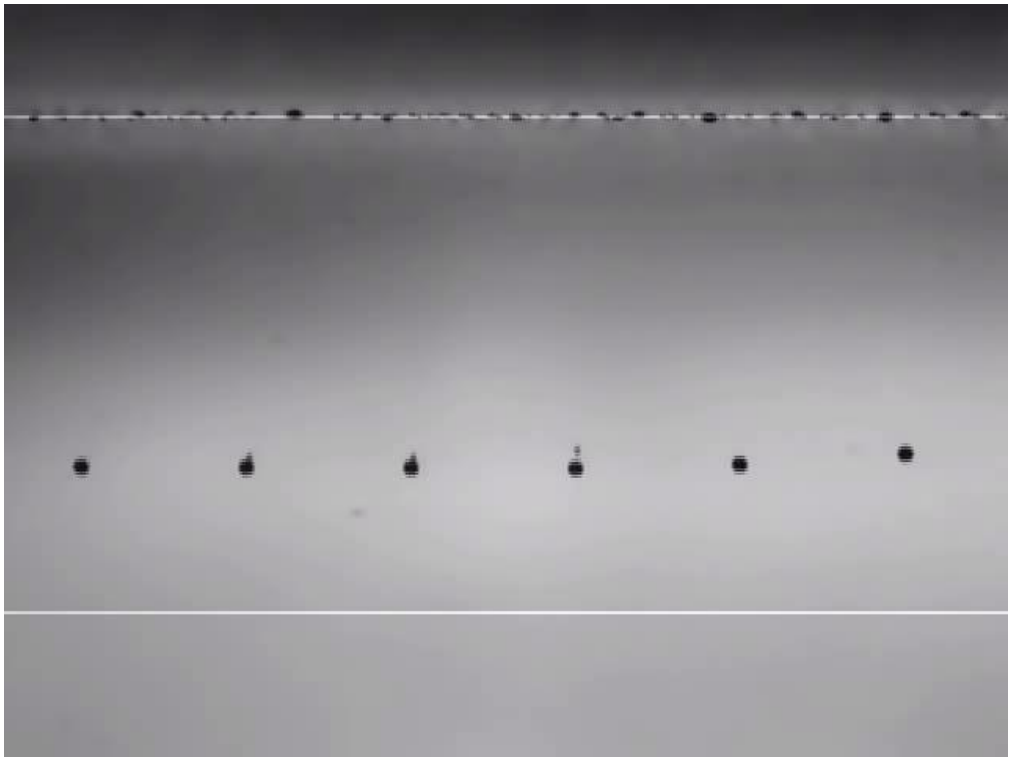
Water-repellent film

Estimation for ink discharge properties

《 ink chamber element 》

State of the Ejected Ink Droplets

Multi-Volume: 1.5 / 3.0 / 13 (pl)

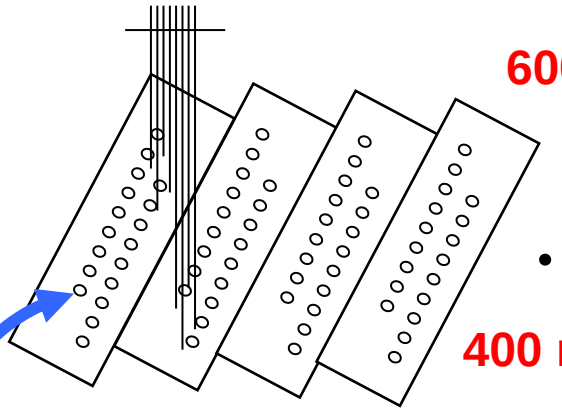


Accurate and stable drop control

Structure of Line Lead Device

●High resolution

Single head



600 dpi pitch
(’04～)

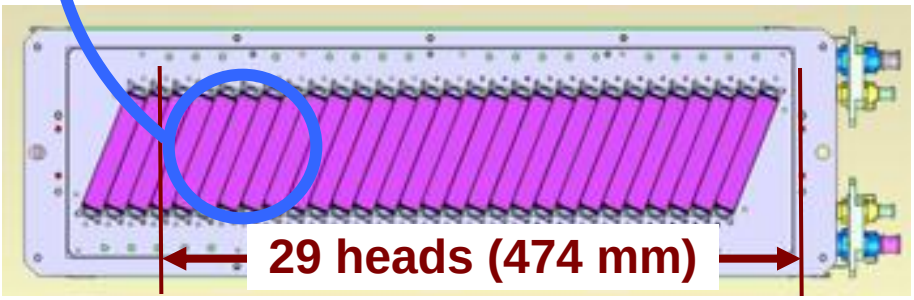
.....

400 nozzles each
(’04～)

1200 dpi pitch
(’08～)

800 nozzles each
(’08～)

Line head device



Sending direction
of the printed matter

●High speed

60 m/min
(’04～)

150 m/min
(’08～)

On-demand Printer and Line Head Device

Single head

800 nozzles

Line head device

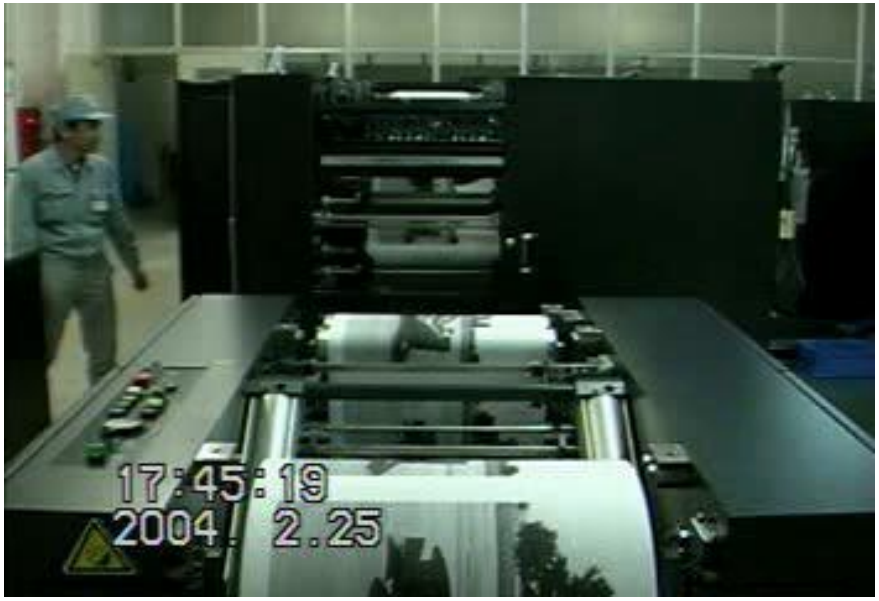
29 heads

On-demand printer

- High printing speed
- Large printing width

● Industrial-scale printed matter (Bills, DMs, Education texts)

State of Printing by On-demand Printer



Miyakoshi (2004)

600 dpi, 60 m/min

Impika (2010)

1,200 dpi, 152 m/min

- ◆High resolution
- ◆High speed
- ◆Large width

Table of Contents

Future Applications

CAR

AVC

DSC

Phone

Game

Navigation

Printer

Control

Motion Sennsor

Angular Rate Sensor

Ink Jet Head

Display

Combine Sensor

PZT/Si Film

Mirror Device

Speaker

Energy Harvesting

Robot

Hearing Aid

Pump

Power Source for Sensors

MicroTAS

RoHS Directive

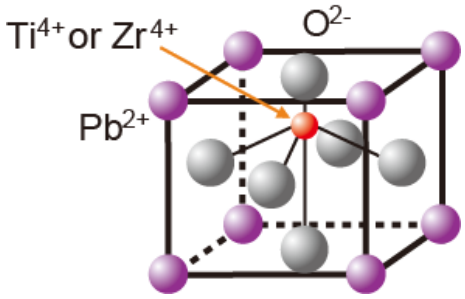
Health Care

Energy

Lead-Free Device

Table of Contents

Lead-Free Piezoelectric Material



PZT

Enviroment pollution, RoHS / ELV directives

Lead-free piezoelectric material

Material	$-d_{31}$(pm/V)	Temp. properties	Material stability
PZT（Ref.）	170 (Ceramic, PZT-5A)	Stable until T_C=365℃	Stable in air
$BaTiO_3$	80 (Ceramic)	Stable until T_C=120℃	Stable in air
$(K,Na)NbO_3$	150 (Ceramic, LF4)	Unstable around R.T.	Deliquescence of K
$(Na,Bi)TiO_3$-$BaTiO_3$ (NBT-BT)	40 (Ceramic)	Stable until T_d=150℃	Stable in air

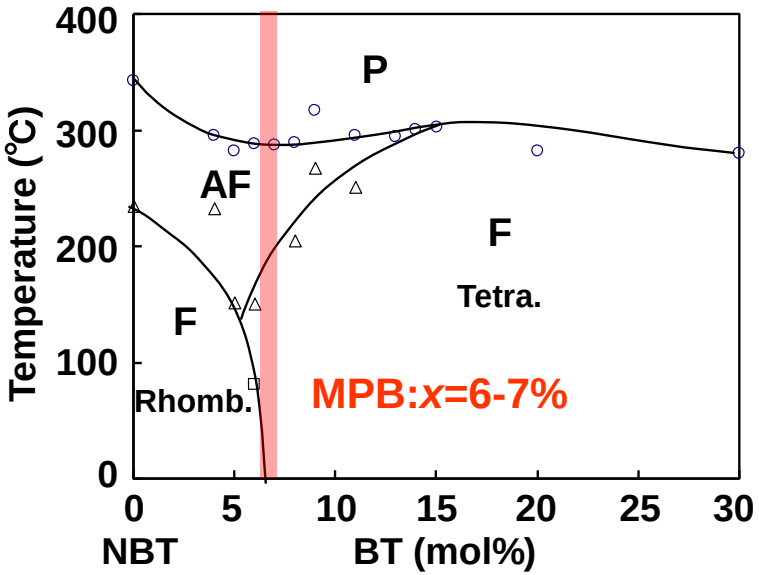
◆$(Na,Bi)TiO_3$-$BaTiO_3$ (NBT-BT) was selected as a R&D target due to good material stability and stable temperature property

Characteristics of NBT-BT Ceramics

◆MPB* is formed between Rhomb. NBT and Tetra. BT

*Morphotropic phase boundary

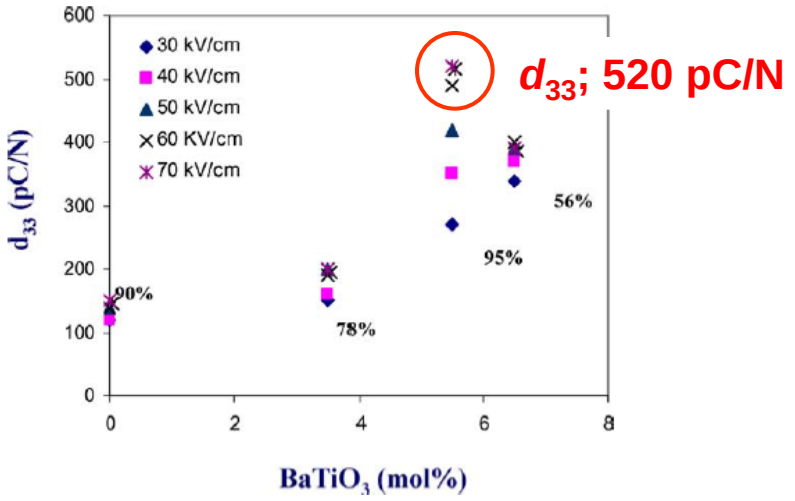
<Phase diagram of (1-x)NBT-*x*BT>



T. Takenaka *et al., Jpn. J. Appl. Phys*. 30 (1991) 2236.

◆Piezoelectric constant is strongly dependent on crystal orientation

- d_{33}= 125 pm/V (Ceramic)
- d_{33}= 520 pm/V (<001> Ceramic)



H. Yilmaz *et al., J. Electroceram.* 11, 217 (2003).

We fabricated NBT-BT films around MPB composition, and investigated into crystal structure, piezoelectric properties.

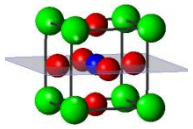
Preparation of NBT-BT Films

Sputtering conditions

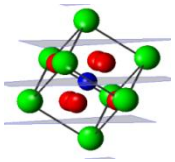
●Target:	(1-x)(Na,Bi)TiO_3 + x$BaTiO_3$ ［x=0.00～0.15］
●Substrate:	MgO(100), (110), (111)
●Temperature:	600 ~ 700 ˚C
●RF Power:	1.5 ~ 2.0 W/cm^2
●Gas Pressure:	0.6 ~ 0.8 Pa
●Deposition Rate:	5 ~ 10 nm/min
●Bottom electrode:	Pt

●Film Thickness : 3 μm

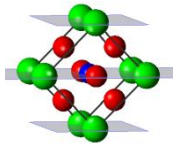
Epitaxial Growth of NBT-BT Films on MgO



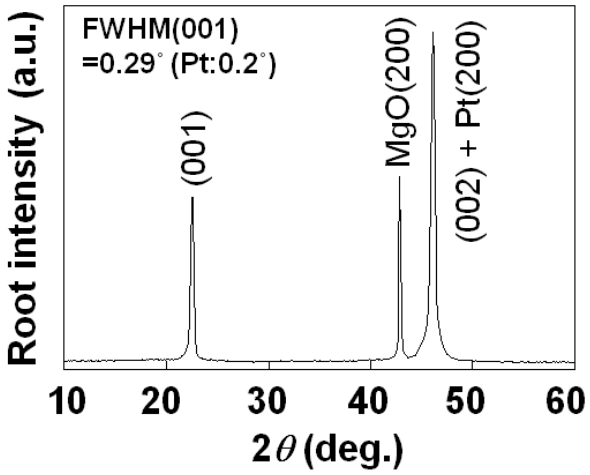
(001) Orientation

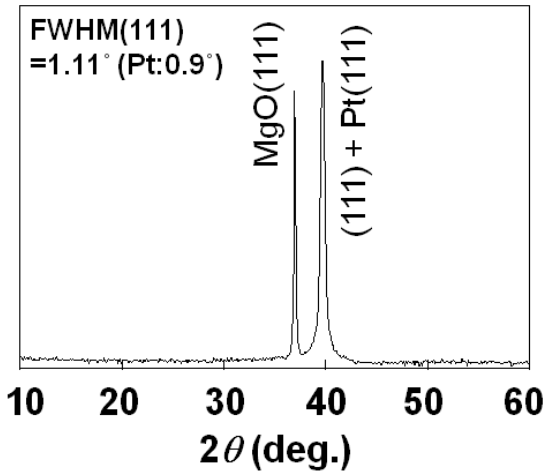


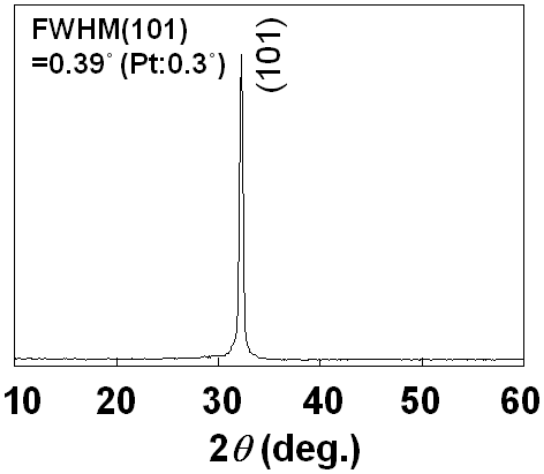
(111) orientation

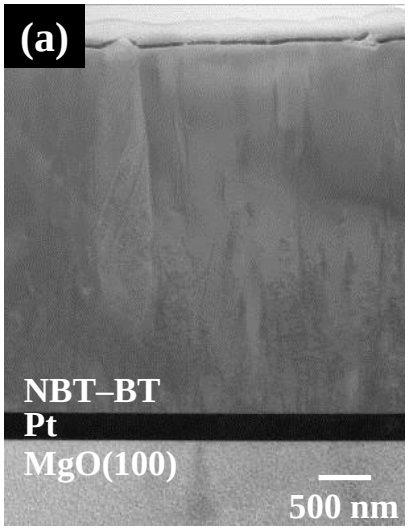


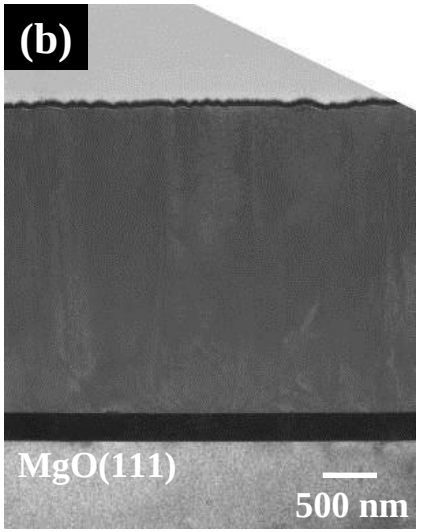
(110) orientation

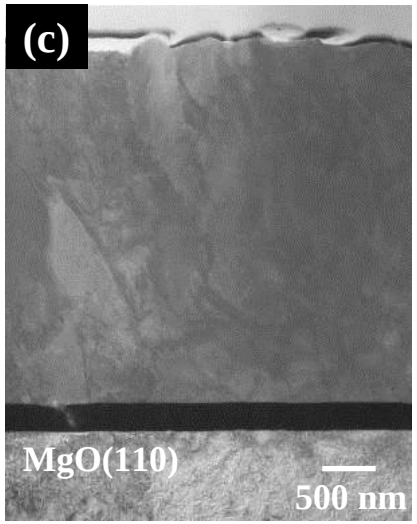




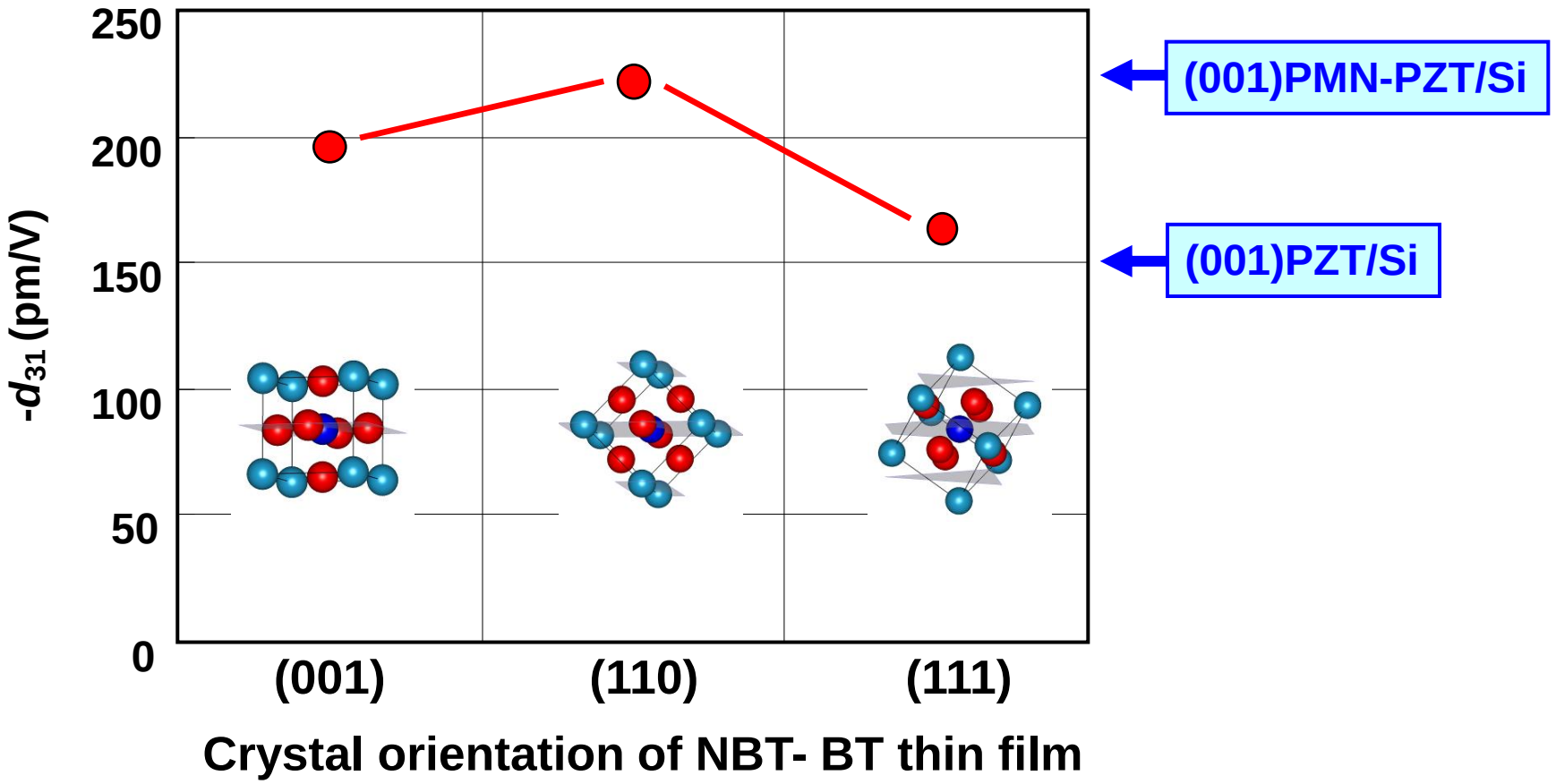








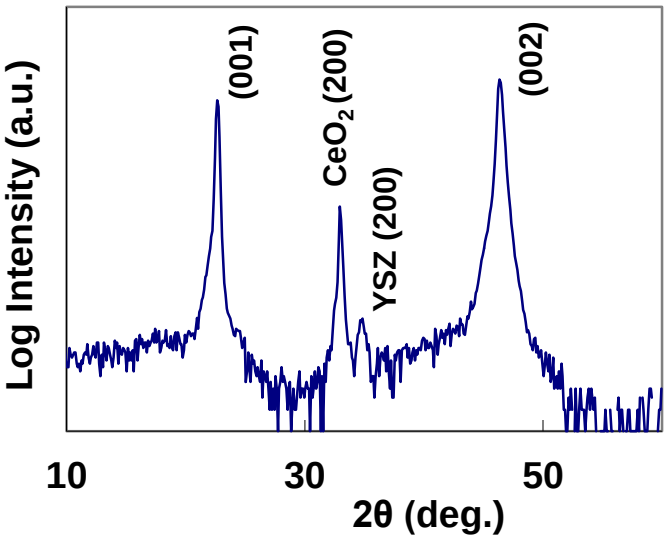
Properties of NBT-BT Films on MgO

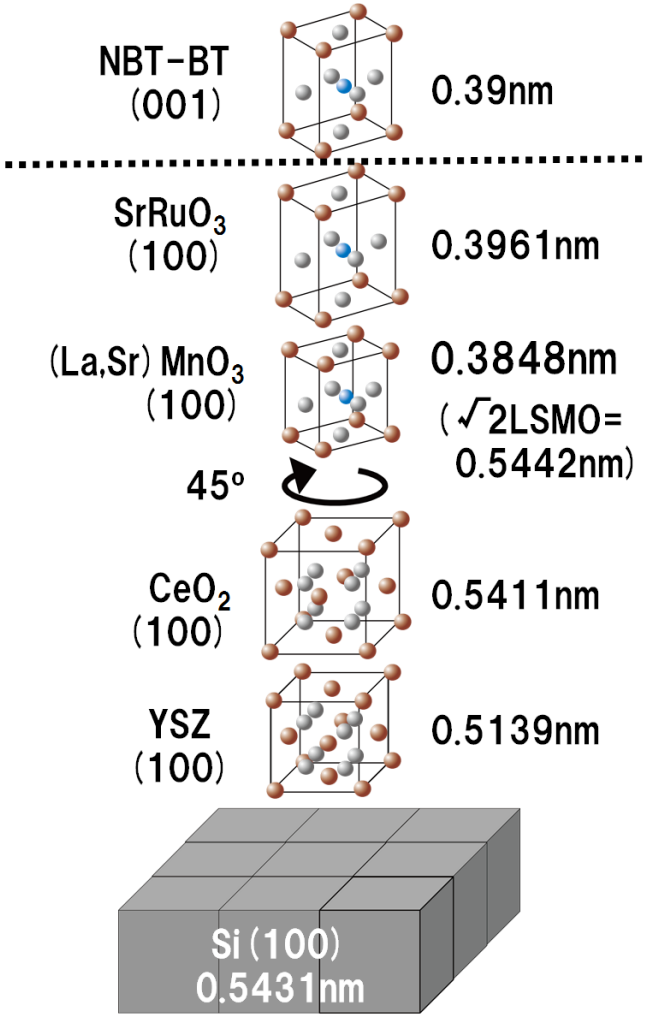


Y. Tanaka, *et al.*, J. Am. Ceram. Soc., 95, 3547 (2012)

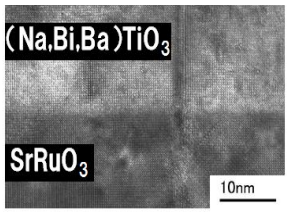
NBT-BT thin films are promising lead-free replacement for PZT-based applications.

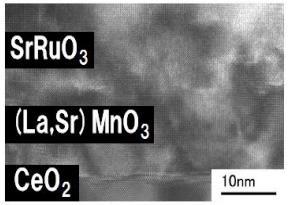
Epitaxial Growth of NBT-BT Film on Si

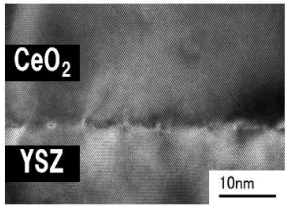


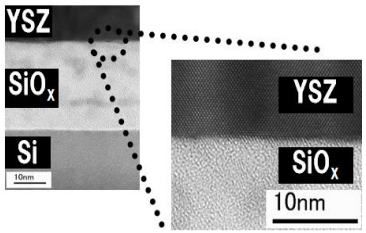


TEM images









-d31	97 (pm/V)
ε_r	493
tanδ	0.06

Table of Contents

Summary

1. (001)-PZT films were deposited on Si by RF magnetron sputtering

   $-d_{31}$ = 150pm/V(PZT), 225pm/V(PMN-PZT)

2. PZT films on Si were applied to

   a. Angular rate sensors for car navigation systems and DSC

   b. Actuators for inkjet printer heads

PZT and PMN-PZT films on Si are suitable for sensors and actuators in micro-electro-mechanical systems (MEMS)

3. Lead-free NBT-BT epitaxial films were fabricated on MgO and Si

   MgO: $-d_{31}$ = 195pm/V(001), 221pm/V(110), 162pm/V(111)

   Si: $-d_{31}$ = 97pm/V(001)

Thank you very much

for your attention.