Piezoelectric MEMS: Materials, Devices, and Applications

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Outline

• Piezo-MEMS devices today
  – companies & foundries in the market today
  – products on the market today
  – Comparison of piezo materials: PZT & AlN

• Future piezo-MEMS devices
  – Piezoelectric micromachined ultrasonic transducers (PMUTs)
  – Air-coupled devices for ranging & gesture sensing
  – Fluid-coupled devices for biometrics
Horsley Group Research

Optical MEMS

Ultrasonics

Gyro & magnetometer

Advanced sensors

Current Research Activities

New materials & fabrication

Microactuators

Si \( \mu \)fluidics

Diamond MEMS

Design & automation

Magnetic MEMS

Si Rotor

Liquid droplets

Diamond Wineglass Resonator 1 mm

Diamond

Silicon

10 kV 50 \( \mu \)m x800

60 \( \mu \)m
Piezoelectric MEMS

Commercialization Status
Film Bulk Acoustic Resonators (FBAR)

LTE Band Duplexer (Avago)

- Avago produces 1 Billion AlN FBAR’s per year.
IDT: Timing Oscillators

Images: Harmeet Bhugra, IDT
Other Commercial Piezo-MEMS Devices

Microgen Energy Harvester

Panasonic Gyroscope

poLight Varifocal Lens
Thin Film PZT – Sensors & Actuators
Players roadmap – expected year for market entry

Expected year of foundry service readiness for thin film PZT technology
Piezoelectric Materials

Mechanical strain $\leftrightarrow$ electrical polarization

$$D = eS + \varepsilon^{TE}$$

Piezoelectric coefficients  dielectric permittivity

electric displacement  strain  electric field

$e = cd$

d: [pm/V]

e: [C/m²]
## Comparing Piezoelectric Materials: Materials for Acoustic Transducers

<table>
<thead>
<tr>
<th>Metric</th>
<th>Property</th>
<th>Units</th>
<th>AlN</th>
<th>PZT</th>
<th>ZnO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmitter</strong></td>
<td>$e_{31,f}$</td>
<td>C m$^{-2}$</td>
<td>-1.05</td>
<td>-14.9</td>
<td>-1.0</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$\varepsilon_{33}$</td>
<td>-</td>
<td>10.5</td>
<td>1020</td>
<td>10.9</td>
</tr>
<tr>
<td><strong>Receiver</strong></td>
<td>$e_{31,f} / \varepsilon_{33}\varepsilon_0$</td>
<td>GV/m</td>
<td>-11.3</td>
<td>-1.64</td>
<td>-10.3</td>
</tr>
<tr>
<td>Sensitivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[S Trolier-McKinstry & P. Muralt, J. Electroceram. 12(7-17), 2004.]
AlN Deposition: Reactive Sputtering

- Deposition rate > 50 nm/min
- Low substrate temperature: 400°C
- Bottom electrode materials: Mo, Pt, Al
- AlN crystalline structure characterized by XRD Rocking Curve
  - Typically ~1.5° FWHM for highly c-axis oriented film
Piezoelectric Micromachined Ultrasonic Transducers (PMUTs)
Ultrasonic MEMS: Current Research Areas

• Air-coupled PMUTs
  – Diameter ~0.5 mm
  – Operating frequencies: 40 kHz – 800 kHz
  – Applications: gesture recognition, ranging, autofocus, gas metering

• Fluid-coupled PMUTs
  – Diameter ~50 microns
  – Operating frequencies: > 10 MHz
  – Applications: medical imaging, biometrics (fingerprint sensing)
Ultrasound Applications

- Medical imaging
- Ranging/obstacle avoidance
- Robotics
- Non destructive testing
- Gesture recognition
Existing Ultrasound Transducers

- **Advantages:**
  - Large output pressure
  - Directional, if desired

- **Disadvantages:**
  - Inefficient coupling to air
  - Matching layers required
  - Too big for consumer electronics
  - Dumb sensor. Lots of external electronics required.
Micromachined Ultrasound Transducers

- Suspended plate structure
- Increased coupling due to low acoustic impedance
- Array fabrication possible
- Micro-scale features
Air-Coupled Acoustic Transducers

Want:

• Large output pressure despite air’s low acoustic impedance
  → Large transducer displacement
  → Piezoelectric Actuation

[Shelton et al., 2009 IEEE Ultrasonics Symp.]
[Przybyla et al., IEEE Sensors J. 2011]
Aluminum Nitride (AlN) PMUT Cross Section

- **Al**
- **AlN**
- **Mo**
- **2μm**
- **1μm**

- **250μm**
- **450μm**

- **BW ≈ 10 kHz**
- **fo ≈ 200 kHz**
Chip-Scale Arrays Enable 3D Ranging

- 2D array of transducers:
  - Output power on-axis: $N^2$
  - Number of elements sets beam width
    - Beam width $\sim 180^\circ/N$ for linear array
  - Individual electrodes enable electrical beam steering
  - Spacing $\sim \lambda/2 = 0.9\text{mm}$ for $180^\circ$ beam steering
Phased Arrays are Directional

Narrow beam improves SNR & spatial resolution

Phased Arrays are Directional

Output SPL Scales with N

Narrow beam improves SNR & spatial resolution

Measured Data
Linear Fit

Number of Transducers
Relative Output Pressure (a.u.)

Range Measurement – Received Signal

\[ \sigma_r \approx 1\text{mm} \]
Range Resolution

Voltage

$\Delta r \approx 25$mm
Single Pulse Image

For 1 m max range design, @50 cm:

- Z-axis: 0.4 mm rms
- X-axis: 0.2° rms
- Y-axis: 0.8° rms

www.chirpmicro.com
Ultrasonic Fingerprint Sensor

• Requires PMUTs similar to medical transducers
  – Center frequency > 20 MHz
  – 50 μm resolution
• Significant performance advantages over existing fingerprint sensors
  – Sub-surface dermal imaging.
  – Wet/dry fingers can be imaged.
State of the art: Commercial Ultrasonic Fingerprint Sensor

Pros:
- Dermal detection

Cons:
- Large system
- Mechanical scanning

Reference: Ultra-scan®, U.S. patent 5224174
Bulk Piezo Fingerprint Sensors

**Drawbacks:**

- Interconnect is challenging
- Readout based on resonator Q (no advantage over capacitance)
- High manufacturing cost

Sonavation Inc.
72 x 9 PMUT Array

Cross-section of 40 µm PMUT

Coupling the Array to Skin

Test Setup

Concept

Hydrophone

Fluid

PDMS 250 µm

Polyethylene

PDMS

Test Setup Concept
Mapping the Pressure Field

40 μm Needle Hydrophone

PMUT Array

x/z

x/y
Experimental Beamforming: AlN PMUTs

15 elements/8 channels, 140 µm Pitch

12V input
15 elements
8 channels
140 µm pitch
System diagram: pulse-echo imaging

PMUT Array

Phantom: imaging target
Ultrasonic transducers
Fluid coupling material

1.8V supply
32V

FPGA
Number of pulse cycles
Time delay control
Input frequency

ASIC

Transmitting wave
Echo wave

Collaboration w/ Bernhard Boser, UC Berkeley
1 D ultrasonic imaging

Pulse echo
Envelope

100 µm scanning step
2 D Scanning

X scanning step 150 µm
Y scanning step 200 µm
Summary & Conclusions

• **Current piezo MEMS devices:**
  - Several piezo-MEMS devices are now in high volume production.
  - Growing maturity of manufacturing base will enable new devices.

• **Future piezo MEMS devices: PMUTs**
  - Today’s ultrasound sensors lack capabilities for consumer electronics applications.
  - **In air:** Tiny 0.5 mm PMUTs have up to 1 m range.
  - **In tissue:** pulse-echo imaging demonstrated w/ 1.8V supply.
  - PMUTs are a disruptive technology for gesture sensing and biometrics.
Acknowledgements

• **Prof. Bernhard Boser’s group (UC Berkeley)**
  – Richard Przybyla, Hao-Yen Tang, Igor Izyumen

• **Horsley group (UC Davis)**
  – Stefon Shelton, Yipeng Lu, Ofer Rozen, Andre Guedes, Stephanie Fung

• **Sponsors**
  – NSF & DARPA
  – Texas Instruments
  – Invensense
  – Capella Microsystems
  – Qualcomm