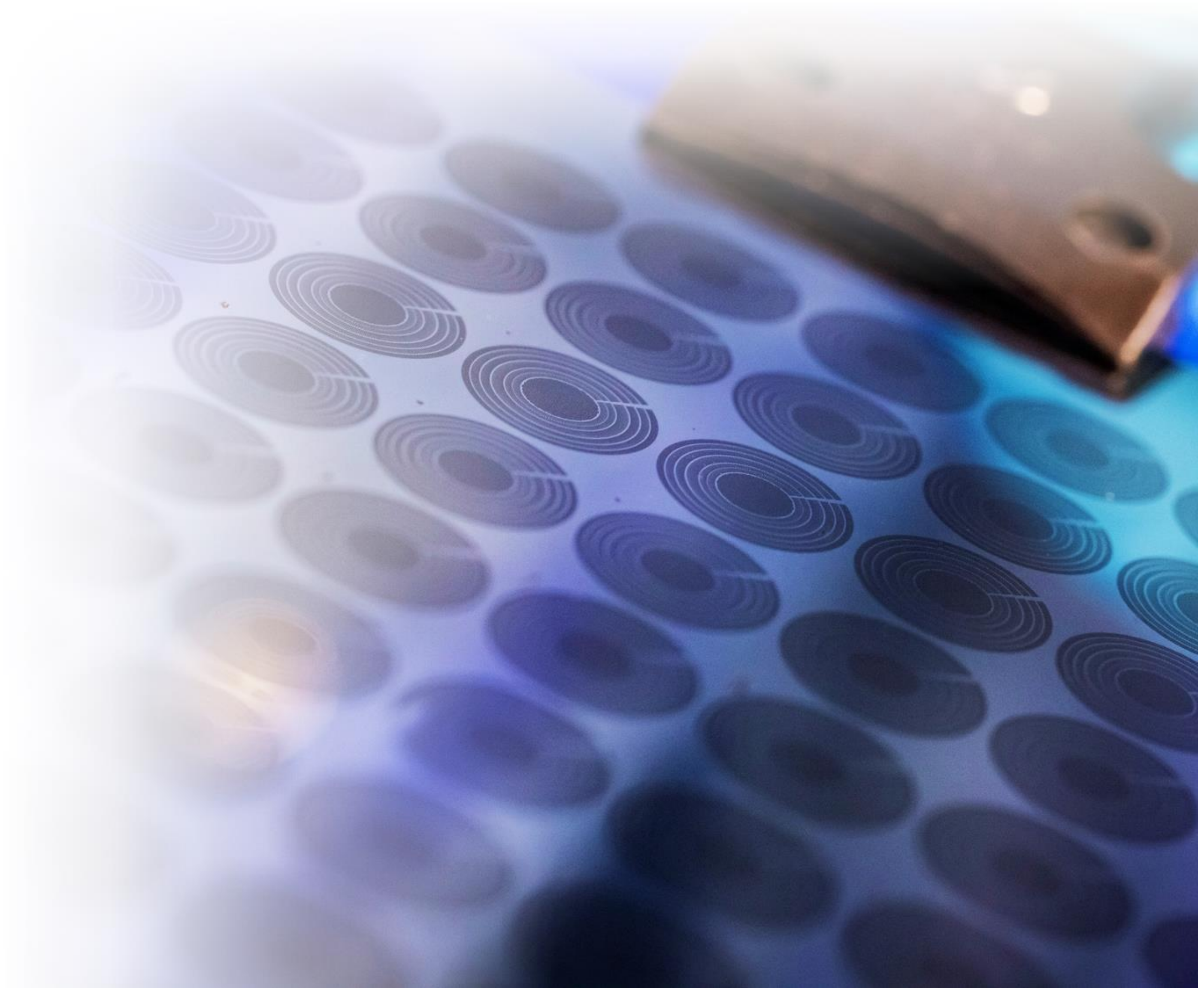
PMUT Technology: Compact and Energy-Efficient Microtechnology Solutions for Ultrasonic Sensing



Contact:

Katja Meinel
E-Mail: katja.meinel@enas.fraunhofer.de
Phone: +49 371 45001 444

Chris Stoeckel
E-Mail: chris.stoeckel@zfm.tu-chemnitz.de
Phone : + 371 531 32628

Abstract

Piezoelectric micromachined ultrasonic transducers (PMUTs) using aluminum nitride (AlN) as the active piezoelectric layer represent a powerful, compact, and energy-efficient alternative to conventional bulk piezoelectric elements. Due to their CMOS compatibility, high mechanical robustness, and strong potential for miniaturization and integration, AlN-based PMUTs are particularly well suited for use in portable devices, medical diagnostics, and industrial inline measurement systems. Their fabrication using established MEMS processes also enables cost-effective scalability and seamless system integration. This white paper provides an overview of the technological fundamentals, key advantages, and potential applications of these innovative ultrasonic transducers, highlighting their relevance for future developments in ultrasonic sensing.

1. Introduction

Ultrasound technology is currently undergoing a fundamental transformation, shifting away from bulky, discrete components toward highly integrated, miniaturized systems. In particular, micromachined ultrasonic transducers (MUTs) are enabling entirely new applications in fields such as medical technology, automotive systems, and consumer electronics due to their compact design. MUTs generate acoustic signals using microscale membranes; these signals can be analyzed through reflection and interaction with objects for both imaging and sensing purposes. When arranged in arrays, MUTs enable spatially resolved detection and high-resolution ultrasonic and photoacoustic imaging.

The development of piezoelectric MUTs provides powerful, CMOS-compatible alternatives to traditional bulk piezoelectric elements. AlN has proven to be a particularly well-suited active piezoelectric material, offering excellent thermal stability, low dielectric losses, and outstanding process compatibility with modern silicon technologies.

The PMUTs presented in this paper are based on silicon-based membranes and utilize AlN for the generation and detection of ultrasound from the kilohertz to megahertz ranges. Fabricated using established, wafer-based MEMS processes, they enable highly miniaturized, scalable, and cost-effective production. Thanks to their compact size, low operating voltage, and high integration capability, these PMUTs are ideal for use in portable devices, industrial inline measurement systems, and medical diagnostic equipment.

A key differentiator of our technology is its modular platform architecture, which allows for the flexible adaptation of chip dimensions and acoustic channels to meet specific requirements. This enables the realization of customized solutions for applications where compact form factor, energy efficiency, and system integration are critical. The presented AlN-based PMUTs provide a future-ready technology platform for the next generation of smart ultrasonic sensing systems.

2. Operating Principle and Fabrication

PMUTs consist of numerous oscillating membranes that generate ultrasonic waves. Their operation is based on the unimorph principle, wherein a piezoelectric layer is bonded to a thin, flexible silicon membrane. When an electrical voltage is applied, the membrane deforms due to the inverse piezoelectric effect, generating ultrasonic waves. Conversely, an incoming acoustic wave causes mechanical deformation, which is then converted into an electrical signal. This dual functionality enables both the transmission and reception of ultrasound signals.

In contrast, capacitive systems require variable capacitance in the form of an air or vacuum gap. This introduces physical limitations to capacitive systems in the form of the use of DC bias and nonlinear transducer principles, as well as high sensitivity to environmental disturbances on the membrane and gap, such as thermal mismatches and external forces (e.g. those introduced by packaging layers and interaction with samples). Piezoelectric ultrasonic transducers do not have these physical limitations, which makes them highly linear, reliable and temperature stable, as well as plug-&-play ready with market available ultrasonic electronics.

Fabrication is carried out on 150 and 200 mm SOI wafers using established MEMS technologies. After the thermal growth of a silicon dioxide (SiO_2) layer, a thin layer of silicon nitride (Si_3N_4) is deposited. The mechanical stress of this layer is carefully matched to that of the AlN piezoelectric layer to minimize membrane curvature. A titanium/platinum stack follows, Ti serves as an adhesion layer between Pt and SiO2. Pt serves as a bottom electrode as well as a seed layer for AlN. The piezoelectric AlN layer is then deposited, followed by a patterned aluminum top electrode. Finally, selective back-side etching of the silicon wafer releases the membranes.

The entire process is fully compatible with standard MEMS fabrication techniques and supports high levels of miniaturization and cost-efficient volume production. Figure 1 shows a cross-section of a representative PMUT cell along with its corresponding layer stack.

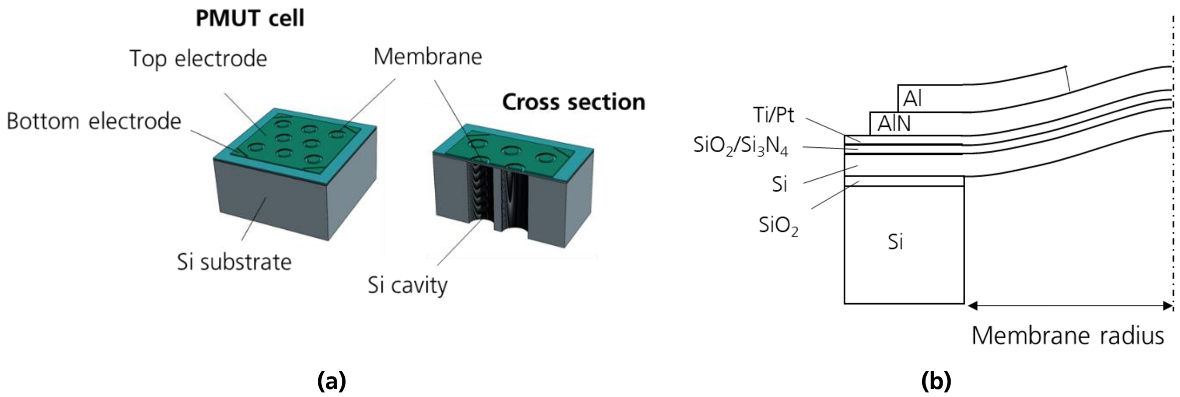


Figure 1: Structure of the PMUTs: (a) Cross-section of a representative PMUT cell; (b) Corresponding layer stack.

3. Performance data for different PMUT variants

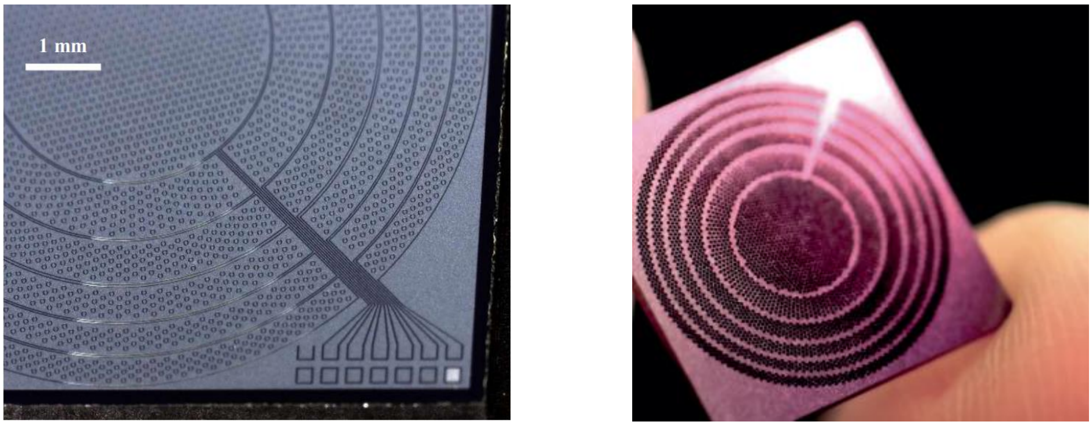
3.1. Ring-Array PMUTs

The "Ring-Array PMUTs" consist of a total of 4,018 circular membranes, arranged in six concentric ring structures that form six independent acoustic channels, with 588 to 801 membranes per ring. Each membrane has a diameter of 100 µm (see Figure 2). In contrast to classical linear PMUT arrays, this design enables a uniform radial distribution of acoustic elements and facilitates the scalable adaptation of the layout to different ring and membrane geometries.

Shielding structures are integrated between the individual rings to minimize electrical crosstalk and to allow independent signal control of each ring. Within each ring, the membranes are connected by radially oriented conductor paths, resulting in a compact layout and efficient electrical interconnection. This configuration yields a fill factor of 42 % within a chip diameter of 10 mm^2, offering a well-balanced trade-off between active area and mechanical stability.

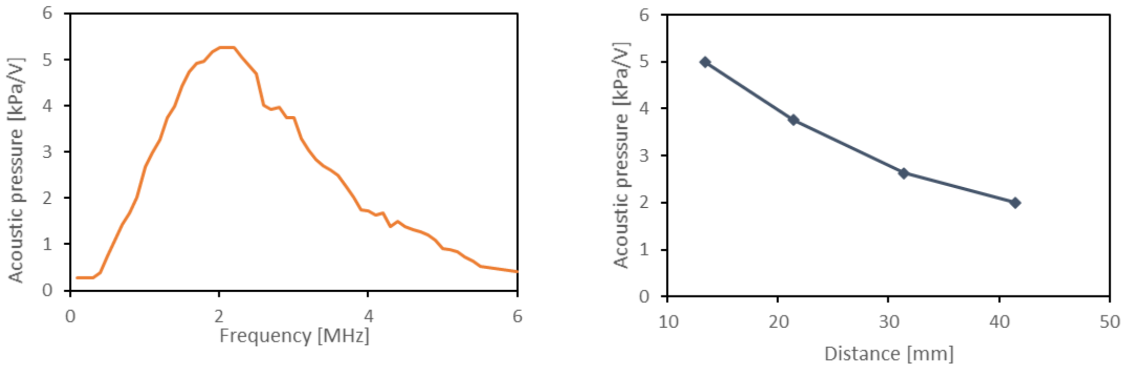
The ring-array concept is particularly well suited for applications that require radially symmetric acoustic emission or a circular sensor arrangement. Potential use cases include liquid level measurement, object detection, fluid characterization, and non-destructive testing.

Figure 3 shows the frequency response of a representative PMUT operated in a liquid environment. The transducer achieves an acoustic pressure of 5 kPa/V at a distance of 13 mm. The corresponding resonance frequency is approximately 2.1 MHz.



(a) **(b)**

Figure 2: Ring-Array-PMUTs: (a) Microscope image of a PMUT chip on wafer level; (b) Photography of a diced chip.



(a) **(b)**

Figure 3: Acoustic signal of an exemplary Ring-Array-PMUT (1 channel) in liquid, recorded by hydrophone.: (a) Frequency response curve; (b) Transmission efficiency versus distance.

Table 1: Specifications of the Rind-Array PMUTs.

Specification	**Unit**	**Value**
Chip dimension	mm^2	10 x 10
Resonance frequency (air)	MHz	3.9 ± 0.2
Resonance Frequency (liquid)	MHz	2.1 ± 0.2
Bandwidth (liquid)	MHz	0.5 – 4.5
Bandwidth (liquid)	%	~100%
Capacitance (per channel)	nF	1.6 ± 0.2
Channels		Up to 6 (ring channels)
Actuation voltage	V	5 – 100
Acoustic pressure/channel (at 13 mm)	kPa/V	5.0

3.2. PMUTs with adaptive channel geometry ("Universal PMUTs")

The "Universal PMUTs" are designed as a versatile platform to address the requirements of a wide variety of applications. Their architecture supports operation in both air and liquid environments, making them suitable for distance measurement, configurable multi-channel sensing, and basic imaging tasks. The devices have a total chip area of 10 × 10 mm² and consist of 100 individual cell structures of 1 × 1 mm², each comprising multiple circular membranes.

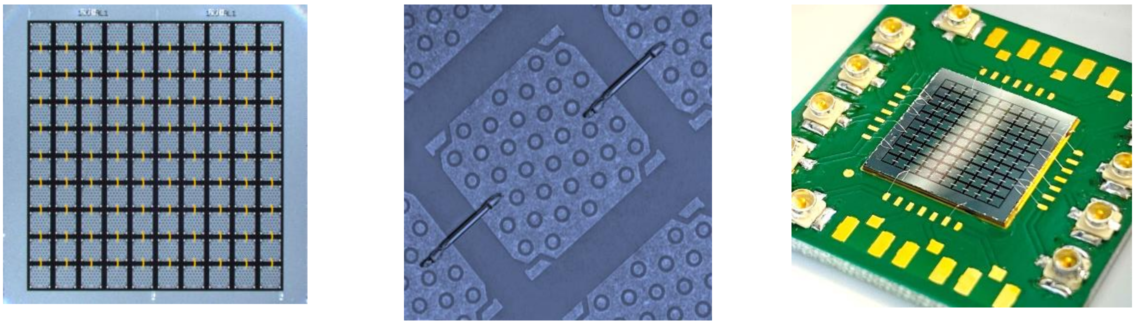
A key innovation of this technology lies in its patented cell architecture, which offers a high degree of application flexibility. Each PMUT cell can be operated independently or interconnected via wire bonding to form arrays.

By adapting the wire bonding layout, the geometry, size, and number of acoustic channels can be freely configured – without requiring any changes to the silicon chip design itself. Whether a linear, circular, or complex array configuration is needed, the PMUT chip can be easily tailored to the specific application using automated wire bonding technology. This post-fabrication reconfiguration of the channel layout enables fast prototyping and modular system integration.

Figure 4*: Microscopic images of a Universal PMUT chip after wire bonding (rectangular strip like geometry): (a); Entire silicon chip; (b) Single cell with wire bonds; (c) Chip with wire bonds on mounted on PCB.*

a and b show microscope images of a representative diced PMUT chip after wire bonding, with a striped geometry used to implement 10 individual acoustic channels. Figure 4*: Microscopic images of a Universal PMUT chip after wire bonding (rectangular strip like geometry): (a); Entire silicon chip; (b) Single cell with wire bonds; (c) Chip with wire bonds on mounted on PCB.*

c illustrates the chip with wire bonds on mounted on PCB.



(a) **(b)** **(c)**

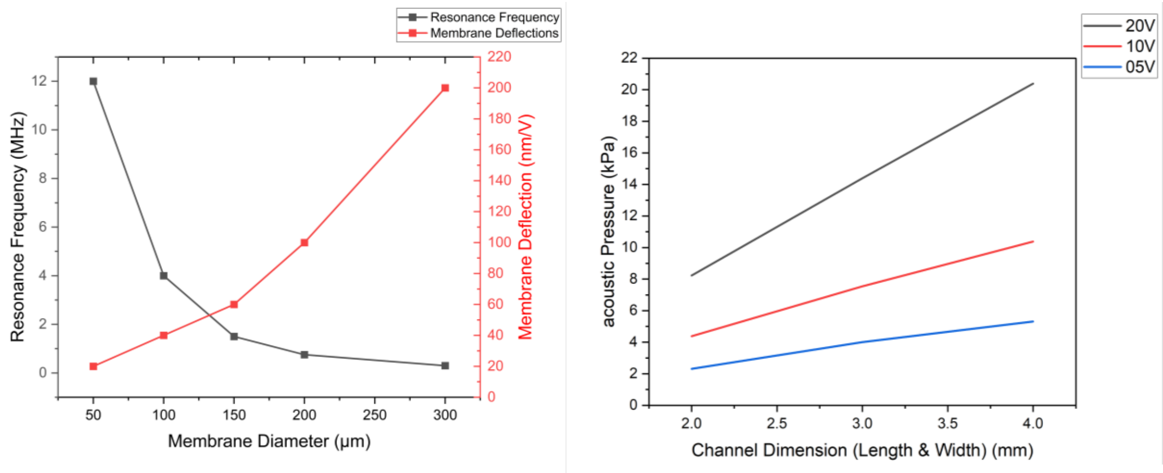
Figure 4: Microscopic images of a Universal PMUT chip after wire bonding (rectangular strip like geometry): (a); Entire silicon chip; (b) Single cell with wire bonds; (c) Chip with wire bonds on mounted on PCB.

To meet the requirements of various application environments (in air or in fluids) membranes with diameters of 50, 100, 150, 200, and 300 µm were fabricated. This variation in geometry allows precise tuning of the resonance frequency and bandwidth, with smaller membranes generally offering higher operating frequencies and broader bandwidths.

Figure 5a illustrates representative results obtained via laser Doppler vibrometry (LDV), showing resonance frequencies and membrane deflections for different diameters. The data clearly demonstrate the dependence of the mechanical response on membrane geometry, highlighting a key design parameter for frequency-selective applications.

To characterize the acoustic output performance, the sound pressure level (SPL) for 100 µm UPMUTs was measured at a distance of 10 mm with an excitation frequency of 1.7 MHz. Figure 5b shows the resulting acoustic pressure as a function of the active channel area and the excitation voltage. The membranes achieve SPLs of up to 172 dB per mm² of chip area and per volt of actuation, confirming the high acoustic efficiency of the system. Table 2: Specifications of the Universal PMUT chip variants. summarizes the Universal PMUT specifications.

Thanks to this high-power density, in combination with the reconfigurable channel architecture, the PMUTs are well suited for precise distance measurements as well as high-resolution ultrasonic and photoacoustic imaging in a variety of media.



(a) **(b)**

Figure 5: PMUT performance: (a) Resonance frequency und membrane deflection over Membrane diameter measured by laser doppler vibrometry; (b) Sound pressure for different voltages versus the active chip area (100µm membrane UPMUTs).

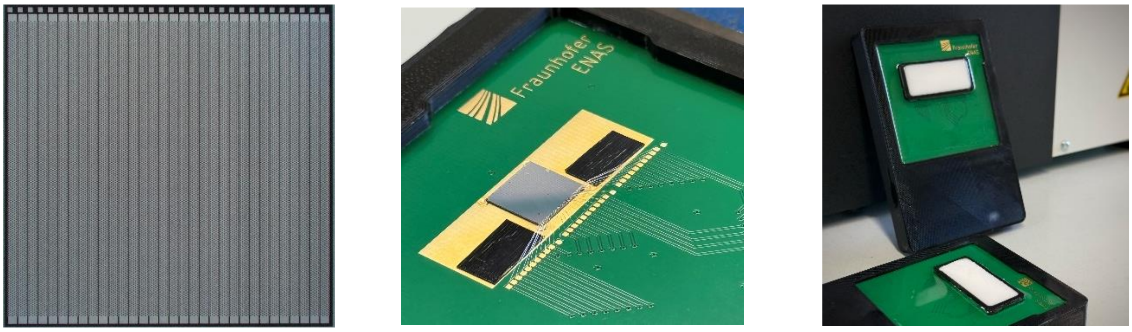
Table 2: Specifications of the Universal PMUT chip variants.

Specification	**Unit**	**Membrane diameter [µm]**			
		50	100	200	300
Chip dimension		1 x 1 mm² to 10 x 10 mm² with a grid size of 1 mm			
Resonance Frequency (air)	MHz	12	3.5	0.75	0.35
Resonance Frequency (liquid)	MHz	7.5	1.9	0.35	–
Bandwidth (liquid)	MHz	3.0 – 12	0.5 – 4.0	0.05 – 2.5	–
Capacitance (per cell)	pF		35	35	
Channels		Customizable (1-10) (Matrix/Strip)			
Actuation voltage	V	5 – 100			
Acoustic pressure/Channel (At 10 mm)	kPa/V	2.34	1.8	–	–

3.3. PMUT Imaging arrays

The "Imaging Array PMUTs" are specifically designed for high-resolution applications, such as photoacoustic imaging, where fine spatial resolution, fast signal acquisition, and array-based detection are essential. The chip has overall dimensions of 9.3 mm × 9.6 mm and consists of 32 acoustic channels, each with a width of 285 µm. Each individual channel houses 660 membranes of 50µm diameter that generate and detect the acoustic waves. The higher number of channels enables faster acquisition, improved resolution, and better signal quality in medical imaging applications especially photoacoustic imaging.

The 32 channel PMUTs were fabricated using the cavity SOI platform, wherein two wafers were initially indivually processed and then bonded together in vacuum at room temperature to form the membranes. Post-wafer bonding, the layer structure is deposited with an AlN active piezo layer, Pt bottom electrode, and Al top electrode. Figure 6a shows microscope images of a 32-channel imaging array PMUT and Figure 6b illustrates the chip with wire bonds mounted on PCB. Figure 6c shows the fully encapsulated 32 channel imaging system for photoacoustic imaging.

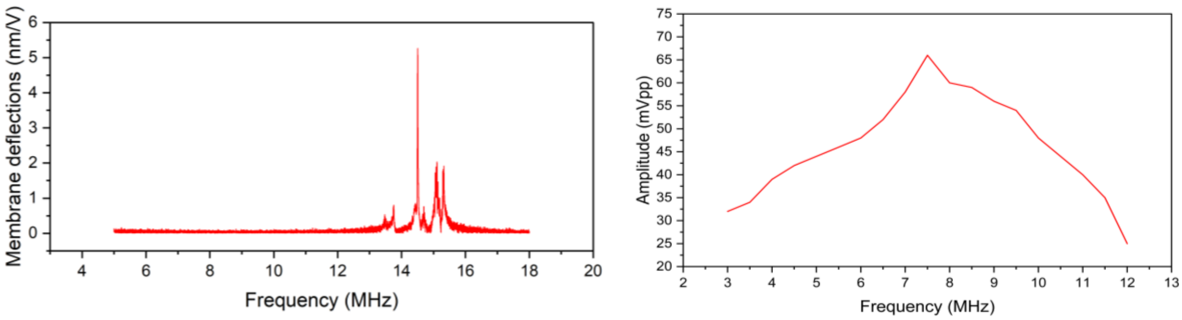


(a) **(b)** **©**

Figure 6: (a) Microscopic images of a 32-channel imaging array PMUT chip; (b) Chip after wire bonding; (b) Fully encapsulated 32 channel imaging system.

PMUTs with membrane sizes of 50 µm were fabricated and subsequently characterized to extract parameters like resonance frequency, technology yield, and acoustic performance using various tools such as Laser Doppler Vibrometry (LDV), white light interferometry, and acoustic hydrophones.

Imaging Array PMUTs operate at a center frequency of 14 MHz in air and exhibit no stress in the membranes post the wafer bonding process. Automated electrical tests were performed to measure the capacitance/channel and accurately determine the yield of the technology platform. These cavity SOI wafers exhibit a >95% technology yield with a capacitance of 220 ± 10 pF per channel. Acoustic tests using a hydrophone in oil were conducted to characterize the acoustic output performance of these PMUTs. Figure 7 shows the frequency response of the 32 channel PMUTs measured with LDV in air and with a hydrophone in oil.



(a) **(b)**

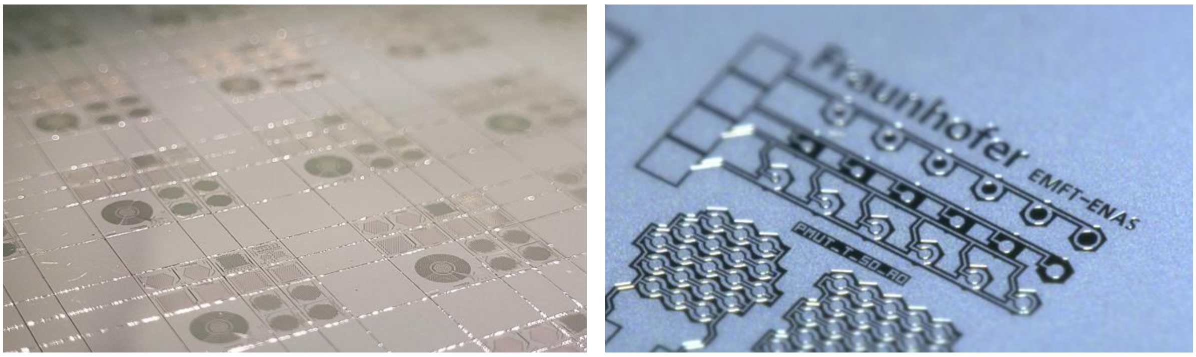
Figure 7: Frequency response measured using (a) LDV in air; (b) hydrophone in oil.

Table 3: Specifications of the 32-channel imaging array PMUT chip.

Specification	Unit	Value
Chip dimension	mm^2	9.3 x 9.6
Resonance frequency (air)	MHz	14 ± 0.5
Resonance Frequency (liquid)	MHz	7.5 ± 0.2
Bandwidth (liquid)	MHz	3 – 12
Bandwidth (liquid)	%	~110%
Capacitance (per channel)	pF	220 ± 10
Channels		32
Actuation voltage	V	5 – 20
Acoustic pressure/channel (at 10 mm)	kPa/V	0.254

3.4. Customized PMUTs

In addition to the PMUTs, which are available for public use, Fraunhofer ENAS and TU Chemnitz offer the possibility to develop customized PMUTs for ultrasonic systems. The R&D services include the simulation and design, fabrication and characterization of PMUTs, as well as packaging and system integration with electronics. In Figure 8, an example for this wafer run (with free use for publications) is shown.



(a) **(b)**

Figure 8: Development of customized PMUTs for as subcontracting or in joint projects for individual specifications: (a) diced chips, (b) microscopic image of a test array with different electrode configurations for inner and outer electrodes.

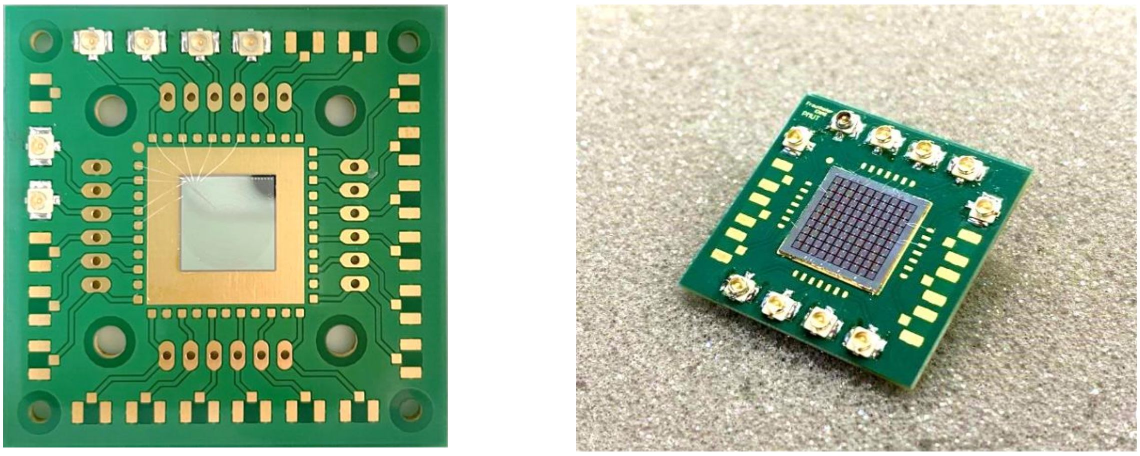
4. PMUT Samples for Evaluation

Evaluation samples for both Ring-PMUTs and Universal PMUTs are available for proof-of-concept testing (see Figure 9 and Figure 10). Standardized samples feature 1 to 10 acoustic channels and sensor sizes ranging from 1 × 1 mm² to 10 × 10 mm² (corresponding to 1 mm² to 100 mm² total area). For Ring-PMUTs, samples with one acoustic channel and sensor sizes from 12 mm² to 75 mm² are also available.

The center frequency depends on the transducer type and typically ranges from 0.5 MHz to 12 MHz, with bandwidths up to 100 %. Ring-PMUT samples typically operate around 0.5 – 4.5 MHz. Additional configurations regarding chip size, channel geometry, and frequency ranges are available upon request.

All evaluation samples can be equipped with an acoustic matching layer and are fully waterproof, enabling operation in both air and liquid media. The PMUT modules are compatible with standard ultrasonic electronics and support direct connection via SMA or BNC adapters. Table 4 shows the specifications of the housed evaluation samples.

Most configurations are in stock or can be delivered at short notice, enabling fast prototyping and integration into test systems.



(a) **(b)**

Figure 9: PMUT samples on PCB for air applications: (a) Ring-Array PMUT; (b) Universal PMUT (10 mm x 10 mm chip size).

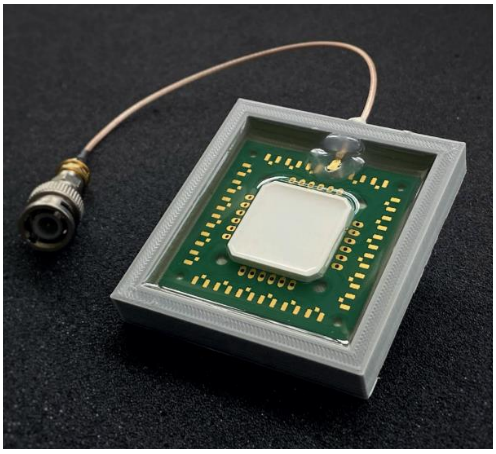


Figure 10: Plug'n'play PMUT evaluation sample for applications in liquid.

Table 4: Specifications of the housed PMUT evaluation sample.

Specification	Unit	Value
Outer dimension (system housing)	mm	60 x 65
Inner dimensions (Silicone chip housing)	mm	25 x 25 mm
Length of cable	mm	100, 200, 300
Connector – SMA/BNC		

5. Conclusion

The development and demonstration of AlN-based piezoelectric micromachined ultrasonic transducers (PMUTs) provides a compact, energy-efficient, and flexibly configurable technology platform for modern ultrasonic sensing. The devices combine high acoustic efficiency, CMOS compatibility, and robust MEMS fabrication processes with a modular architecture that can be tailored to a wide range of applications.

Key design parameters, such as resonance frequency and spatial resolution, can be adapted by adjusting membrane diameters and arranging the membranes in linear, ring-shaped, or planar arrays. Three complementary architectures were demonstrated: **Ring-Array PMUTs** are particularly suitable for applications that require uniform acoustic emission in all directions or circular sensor arrangements; **Ring-Array PMUTs**, suitable for both air and liquid environments and especially advantageous for spatially resolved imaging; and **Imaging Array PMUTs**, specifically designed for high-resolution applications such as photoacoustic imaging.

This design flexibility enables frequency-selective measurements as well as spatially resolved sensing and allows for rapid system integration without modifications to the silicon substrate. The PMUTs achieve acoustic pressure levels of up to 172 dB SPL per mm² and volt, and are suitable for use in both air and fluid environments, making them promising candidates for applications in medical diagnostics, fluid monitoring, and industrial sensing.

The availability of standardized evaluation samples supports a rapid transition from concept to system-level development and fosters the integration of PMUT technology into emerging sensing solutions across research and industry.