Pb-free ScAlN MEMS Array Integrated with 65 nm SiGe CMOS via System-in-Package for Medical Ultrasonic Sensors

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***Abstract*—Conventional medical ultrasonic devices have been dominated by PZT (Pb(Zr,Ti)O_3) [1]. However, Pb-containing materials face strict regulatory restrictions (EU RoHS, REACH, FDA) in in-body medical applications. This work proposes a Pb-free alternative based on ScAlN MEMS arrays, integrated with 65 nm SiGe CMOS using System-in-Package (SiP) technology. The ScAlN MEMS array is designed for 10–50 MHz operation with $\lambda/2$ pitch for high-resolution imaging [2]. The SiGe CMOS front-end integrates LNA, VGA, and ADC, enabling detection of microvolt-level signals. The SiP approach ensures yield separation, short interconnects, and hermetic sealing for medical reliability. Finite element and circuit simulations indicate adequate sensitivity and beam directivity at 20–40 MHz, LNA noise figure < 2 dB, and compact, reliable packaging via flip-chip SiP. Pb-free ScAlN arrays with 65 nm SiGe CMOS via SiP form a practical path for next-generation high-resolution medical ultrasonic sensors.**

***Index Terms*—ScAlN MEMS, Pb-free piezoelectrics, System-in-Package (SiP), SiGe CMOS, Medical ultrasound, Ultrasonic imaging**

I. Introduction

Medical ultrasonic imaging is widely used in ophthalmology, vascular diagnosis, dermatology, and implantable monitoring. Traditional devices have been dominated by PZT due to superior piezoelectric properties [1], but Pb toxicity limits in-body use under EU RoHS, REACH, and FDA regulations. Scandium-doped AlN (ScAlN) has emerged as a Pb-free candidate with CMOS compatibility, high-Q, and industrial adoption in RF BAW/XBAR filters [2]. We propose ScAlN MEMS arrays co-integrated with 65 nm SiGe CMOS via SiP for medical ultrasound.

II. Background and Contributions

A. Background

PZT transducers provide excellent d_{33} and coupling but contain Pb and are not preferred for in-body devices [1]. CMUT/PMUT enable MEMS-CMOS co-integration, yet often require high bias and face fluid-reliability challenges [3]. ScAlN is a promising Pb-free piezoelectric with proven manufacturability and CMOS process compatibility [2]. Combining ScAlN arrays with low-noise SiGe readout via SiP offers a realistic, compliant route to high-resolution ultrasound.

TABLE I
System specifications (ScAlN Array + 65 nm SiGe via SiP)

Parameter	Specification
Operating frequency	10–50 MHz
Array size	64–256 ch (1D/2D)
Pitch rule	$\lambda/2$ (tissue $c \approx 1540$ m/s)
CMOS node	65 nm SiGe BiCMOS
Front-end blocks	LNA, VGA, T/R switch, ADC
ADC resolution	12–14 bit, 50–100 MS/s
System SNR	> 60 dB (20–40 MHz)
Package	SiP (flip-chip)

B. Contributions

- Pb-free ScAlN MEMS array architecture for 10–50 MHz imaging.
- Heterogeneous integration with 65 nm SiGe CMOS via SiP to minimize interconnect and improve SNR.
- FEM/circuit examples indicating adequate sensitivity, beam directivity, and low-noise detection at 20–40 MHz.
- Application considerations in ophthalmology [4], IVUS [5], dermatology, and implantables.

III. System Concept

A. ScAlN MEMS Array

Operation: 10–50 MHz. Channels: 64–256 with $\lambda/2$ pitch. Structures: PMUT-like stacks or BAW/XBAR cavities.

B. SiGe CMOS Front-end

65 nm SiGe BiCMOS with low NF (< 2 dB). Integrated LNA, VGA, ADC, and T/R switch to sense μV-level signals.

C. System-in-Package Integration

Flip-chip bonding integrates MEMS and CMOS dice. Benefits: yield separation, short interconnects, and hermetic sealing.

IV. FEM Analysis Methodology

Finite element simulations were performed to evaluate the ScAlN MEMS array performance. The device stack ($Sc_{0.2}Al_{0.8}N$ piezoelectric layer, electrodes, and supporting membrane) was modeled with piezoelectric solid mechanics,

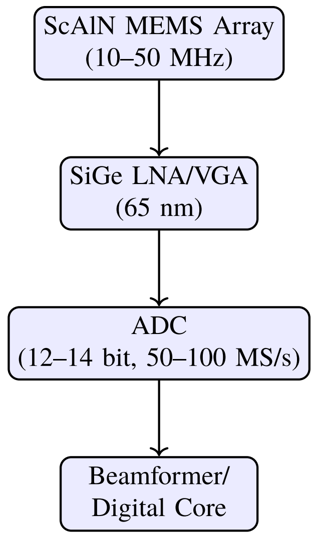

Fig. 1. System architecture (ScAlN MEMS + 65 nm SiGe via SiP).

while the surrounding water domain was represented by acoustic pressure elements with perfectly matched layers (PML) to emulate open boundaries.

Boundary conditions were:

- **Transmit:** Top electrode driven by 1 V AC, bottom electrode grounded.
- **Receive:** Electrodes open, 1 Pa plane acoustic wave applied at fluid boundary.
- **Support:** Membrane rim mechanically fixed.

Material constants were taken from literature for ScAlN ($\rho \approx 3200$ kg/m^3, $\varepsilon_r \approx 11$, $e_{33} \approx 1.3$ C/m^2). Frequency sweeps from 10–50 MHz were conducted to extract impedance, displacement fields, and acoustic pressure radiation.

V. Simulation Results

FEM analysis revealed resonances near 20, 30, and 40 MHz. The simulated electrical impedance showed clear series and parallel resonances; the effective coupling was $k_{\text{eff}}^2 = 2$–4%. In the transmit case (1 V drive), on-axis pressure reached tens of kPa at 1 mm depth. In the receive case (1 Pa input), open-circuit voltage was tens of μV. Combined with the 65 nm SiGe front-end (< 2 nV/$\sqrt{\text{Hz}}$), system SNR exceeded 60 dB across 20–40 MHz (Fig. 4).

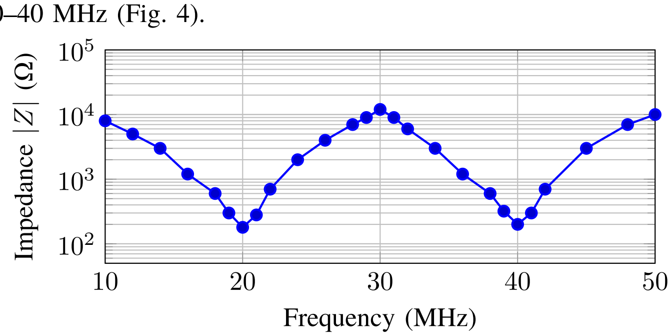

Fig. 2. Impedance magnitude showing resonances near 20, 30, and 40 MHz.

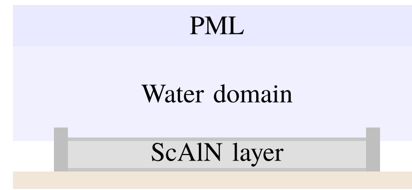

Fig. 3. FEM model sketch: stack, boundaries, and acoustic PML.

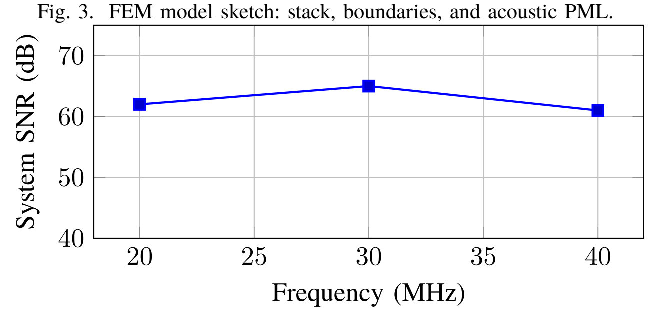

Fig. 4. System SNR with SiGe front-end at 20–40 MHz.

VI. Application Scenarios

- **Ophthalmology:** 20–40 MHz anterior eye imaging [4].
- **Vascular IVUS:** 30–40 MHz catheter arrays [5].
- **Dermatology:** 10–20 MHz skin/tumor imaging.
- **Implantables:** Miniaturized SiP with telemetry.

VII. Discussion

Versus PZT, ScAlN offers CMOS compatibility and Pb-free compliance at lower d_{33}. Versus CMUT/PMUT [3], ScAlN needs lower bias and shows better fluid reliability. SiP yields separation, short interconnects, and hermeticity versus monolithic integration.

TABLE II
Piezoelectric materials for ultrasonic MEMS (summary)

Material	Pb-free	d_{33}	CMOS	Notes
PZT	No	100–500	Low	High performance
ScAlN	Yes	20–30	High	CMOS-compatible
KNN	Yes	80–200	Med.	Bulk ceramic
BNT	Yes	$\sim$100	Med.	High-temp stable
ZnO	Yes	10–15	High	Simple, low d_{33}
PVDF	Yes	5–10	High	Flexible, low output

VIII. Conclusion

Pb-free ScAlN MEMS arrays integrated with 65 nm SiGe CMOS via SiP provide: (i) regulatory compliance, (ii) adequate 20–50 MHz resolution, (iii) low-noise detection via SiGe, and (iv) scalable, reliable packaging. This is a practical, competitive path for next-generation medical ultrasonic sensors.

Acknowledgment

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Author Biography

Shinichi Samizo received the M.S. degree in Electrical and Electronic Engineering from Shinshu University, Japan. He joined Seiko Epson Corporation in 1997, engaging in semiconductor device process development including 0.25–0.18 μm CMOS, HV-CMOS, DRAM, FeRAM. He also contributed to inkjet MEMS process development and thin-film piezo actuator design, leading to the productization of PrecisionCore printheads. His expertise covers semiconductor devices (logic, memory [DRAM/FeRAM/SRAM], high-voltage mixed integration), inkjet actuators, and AI-based control education.