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Ultrasonic Transducers Pmut

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***Next generation medical***

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***imaging technology hinges on the development of cost effective and array compatible transducers making piezoelectric micro-machined ultrasonic transducers (pMUTs) an attractive***

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***alternative to the current bulk piezoelectric technology. This thesis aims to realize pMUT potential starting with the development of an effective single cell model that is further scaled to optimize***

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***multi-cell elements in a 1D array. In the first half of this work, a transverse mode, lead zirconate titanate (PZT) pMUT plate cell is fabricated using common micro-fabrication techniques and a PZT sol-gel***

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***deposition process. Through derivation using a novel Greens function solution technique, an equivalent circuit model with explicitly defined lumped parameters is presented and validated***

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***through electrical impedance measurements of fabricated devices and finite element modeling. The equivalent circuit is a crucial design tool as transducer performance metrics, including***

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***experimentally validated  
acoustic domain values, are  
shown to be defined directly  
from the lumped parameters.  
In the second half, figures of  
merit are identified from these  
performance metrics and an***

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***expanded multi-cell model is employed to strategically target improvements in both bandwidth and coupling while maintaining high pressure output. The resulting, optimized multicell elements***



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***in a 1D array are fabricated via a commercially viable, wafer-scale manufacturing process including a novel PZT dry etch. A top-down fabrication approach facilitates achievement of the largest***

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***active area of a multi-cell  
pMUT to date consisting of  
over 1000 cells in a 200 $\mu$ m x  
4mm element footprint, and  
more substantially, results in  
the highest electromechanical  
coupling recorded for a pMUT***

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***to date measured at  $9 \pm 1.4\%$   
per element.***

***This important text/reference  
presents the first dedicated  
review of techniques for  
contactless 3D fingerprint  
identification, including novel***

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***and previously unpublished  
research. The text provides a  
systematic introduction to 3D  
fingerprint identification,  
covering the latest  
advancements in contactless  
2D and 3D sensing***

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***technologies, and detailed discussions on each key aspect in the development of an effective 3D fingerprint identification system. Topics and features: introduces the key concepts and trends in the***

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***acquisition and identification of fingerprint images, and a range of 3D fingerprint imaging techniques; proposes a low-cost method for online 3D fingerprint image acquisition, and an efficient 3D***

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***fingerprint imaging approach  
using coloured photometric  
stereo; describes pre-  
processing operations on  
point cloud 3D fingerprint  
data, and explains the  
specialized operations for***

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***reconstructing 3D fingerprints  
from live finger scans;  
examines the representation  
of minutiae in 3D space,  
providing details on  
recovering these features from  
point cloud data, and on***



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***matching such 3D minutiae templates; reviews various 3D fingerprint matching methods, including binary surface code-based approaches and a tetrahedron-based matching approach; discusses the***

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***uniqueness of 3D fingerprints,  
evaluating the benefits of  
employing 3D fingerprint  
identification over  
conventional 2D fingerprint  
techniques. This unique work  
is a must-read for all***

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***researchers seeking to make further advances in this area, towards the exciting opportunities afforded by contactless 3D fingerprint identification for improving the hygiene, user convenience,***

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***and matching accuracy of  
fingerprint biometric  
technologies.***

***Fingerprint identification is the  
most prevalent biometric  
technology due to its  
uniqueness, universality and***

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***convenience. Over the past two decades, a variety of physical mechanisms have been exploited to capture an electronic image of a human fingerprint. Among these, capacitive fingerprint sensors***

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***are the ones most widely used  
in consumer electronics  
because they are fabricated  
using conventional  
complementary metal oxide  
semiconductor (CMOS)  
integrated circuit technology.***

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***However, capacitive fingerprint sensors are extremely sensitive to finger contamination and moisture. This thesis will introduce an ultrasonic fingerprint sensor using a PMUT array, which***

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***offers a potential solution to this problem. In addition, it has the potential to increase security, as it allows images to be collected at various depths beneath the epidermis, providing images of the sub-***



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***surface dermis layer and blood vessels. Firstly, PMUT sensitivity is maximized by optimizing the layer stack and electrode design, and the coupling coefficient is doubled via series transduction.***

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***Moreover, a broadband PMUT with 97% fractional bandwidth is achieved by utilizing a thinner structure excited at two adjacent mechanical vibration modes with overlapping bandwidth. In***

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***addition, we proposed waveguide PMUTs, which function to direct acoustic waves, confine acoustic energy, and provide mechanical protection for the PMUT array. Furthermore,***

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***PMUT arrays were fabricated with different processes to form the membrane, including front-side etching with a patterned sacrificial layer, front-side etching with additional anchor, cavity SOI***

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***wafers and eutectic bonding.***

***Additionally, eutectic bonding***

***allows the PMUT to be***

***integrated with CMOS circuits.***

***PMUTs were characterized in***

***the mechanical, electrical and***

***acoustic domains. Using***

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***transmit beamforming, a narrow acoustic beam was achieved, and high-resolution (sub-100 [ $\mu$ m]) and short-range ( $\sim 1$  mm) pulse-echo ultrasonic imaging was demonstrated using a steel***

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***phantom. Finally, a novel ultrasonic fingerprint sensor was demonstrated using a 24x8 array of 22 MHz PMUTs with 100 [ $\mu$ ]m pitch, fully integrated with 180 nm CMOS circuitry through eutectic***

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***wafer bonding. Each PMUT is directly bonded to a dedicated CMOS receive amplifier, minimizing electrical parasitics and eliminating the need for through-silicon vias. Pulse-echo imaging of a 1D***



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***steel grating is demonstrated using electronic scanning of a 20x8 sub-array, resulting in 300 mV maximum received amplitude and 5:1 contrast ratio. Because the small size of this array limits the***

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***maximum image size,  
mechanical scanning was  
used to image a 2D PDMS  
fingerprint phantom (10 mm by  
8 mm) at a 1.2 mm distance  
from the array.***

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***ultrasonic transducers***

***(PMUTs) have greatly***

***advanced in the last decade***

***opening the path to a wide***

***range of applications,***

***including 3D range finding, 3D***

***gesture recognition, 3D***

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***imaging, and fingerprint sensing. This evolving ultrasonic time-of-flight sensors based on microelectromechanical systems (MEMS) technology utilize the flexural vibration of***

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***a membrane consisting of a piezoelectric thin-film.***

***Compared to the conventional bulk ultrasonic transducers, PMUTs are small size, low power consumption, low cost, and easy to fabricate array***

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***structures. Despite many advantages, PMUTs still require further investigation to improve their bandwidth, transmission power, and nonlinear behavior that emerges at large amplitude***

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***excitations. As opposed to the immersed applications, these limitations become particularly significant for airborne applications because they demand large amplitude displacements as well as high***

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***pressure outputs. This work describes various PMUTs designed and fabricated for in-air operation, focusing on each aspect of the issues listed above. In the first part, a method to expand the***



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***bandwidth is presented using lead-zirconate-titanate (PZT) PMUTs. Wideband enables short transmission time that allows detection at a closer distance as well as higher range resolution. By optimally***

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***tuning a small DC bias of 5 V, the rectangular shaped PMUTs demonstrate comparably high bandwidth for air-coupled transducers. The second part focuses on implementing one of the new piezoelectric***

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***materials, a scandium-doped aluminum nitride (ScAlN) thin-film with high Sc concentration at 36%.***

***Retaining many good features of AlN (e.g. CMOS compatibility, low dielectric***

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***loss, high Curie temperature, fairly simple sputtering and etching process), the ScAlN can obtain significantly improved piezoelectric properties up to the crystal phase boundary at 43%. An***

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***optimized design and  
fabrication process for 36%  
ScAlN PMUTs with high  
piezoelectric transduction are  
presented. The transmit  
pressure of these PMUTs  
operating in air at 60 kHz is***

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***105 dB SPL at 10 cm and only 30 dB attenuation at 2 m range. The nonlinear effects of the air-coupled PMUTs are further studied in the third part of the dissertation. An empirical model to predict the***

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***mechanical spring-hardening effect that limits the dynamic range of PMUTs due to the membrane stiffening is proposed and evaluated.***

***Understanding the nonlinear vibration at large amplitudes***

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***allows further improvement in the transducer design especially for airborne applications. Lastly, PMUTs with flexural support structures are presented as one solution to increase the***



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***actuation area and to improve  
the linear operating range.***

***Piezoelectric MEMS***

***Resonators***

***Contactless 3D Fingerprint  
Identification***

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***2009 IEEE 22nd International  
Conference on Micro Electro  
Mechanical Systems (Mems)  
Ferroelectrics***

Sensor Technologies for Civil  
Infrastructure, Volume 1: Sensing  
Hardware and Data Collection

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Methods for Performance

Assessment, Second Edition, provides an overview of sensor hardware and its use in data collection. The first chapters provide an introduction to sensing for structural performance assessment and health monitoring, and an overview of commonly used

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sensors and their data acquisition systems. Further chapters address different types of sensor including piezoelectric transducers, fiber optic sensors, acoustic emission sensors, and electromagnetic sensors, and the use of these sensors for assessing and monitoring civil infrastructures.

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The new edition now includes chapters on machine learning methods and reliability analysis for structural health monitoring. All chapters have been revised to include the latest advances in materials (such as piezoelectric and mechanoluminescent materials), technologies (such as LIDAR), and

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applications. Describes sensing hardware and data collection, covering a variety of sensors including LIDAR Examines fiber optic systems, acoustic emission, piezoelectric sensors, electromagnetic sensors, terahertz technologies, ultrasonic methods, and radar and millimeter wave technology

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Covers strain gauges, micro-electro-mechanical systems (MEMS), multifunctional materials and nanotechnology for sensing, and vision-based sensing and lasers  
Includes new chapters on machine learning methods and reliability analysis

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The use of lithium niobate in signal filtering in TV sets and video cassette recorders is well established and it is finding increased application in optoelectronic modulation devices in DWDM (dense wavelength division multiplexing) fibre optic systems. This fully illustrated volume brings



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electronic engineers, materials scientists and physicists up to date by enlisting the expertise of active researchers and presenting their considered reviews.

Piezoelectric micromachined ultrasonic transducers (PMUTs) have been developed for many applications

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such as biometric identification, medical imaging and gesture recognition as an economic and small replacement for current bulk piezoelectric ultrasonic transducers. The PMUTs fabrication process compatibility to complementary metal-oxide-semiconductor (CMOS) is an

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advantage for making circuit integrated systems in the same process to achieve low cost and small size, especially for mobile and wearable devices. The current PMUTs have no sufficient output pressures compare to bulk piezoelectric ultrasonic transducers. This thesis will focus on

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improving the efficiency of the PMUTs and their arrays from the perspective of piezoelectric materials, individual PMUT structures, arrays designs and the acoustic couplings in the arrays. Firstly, the background of the piezoelectric ultrasonic transducers will be introduced. Comparisons of the

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micromachined ultrasonic transducers (MUT, including piezoelectric and capacitive micromachined ultrasonic transducers) with current bulk piezoelectric ultrasonic transducers show that MUTs have the advantages in the low cost, small size for more potential applications. Then, to

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improve the current performance of the PMUTs, novel piezoelectric materials are utilized to fabricate PMUT arrays. Characterization results indicated that scandium aluminum nitride is a promising thin film for the future PMUT products. Furthermore, the acoustic coupling is a major source

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of the cross talk in the large PMUT arrays and will influence the imaging resolution. An equivalent circuit model is built and verified experimentally to improve the PMUT array designs. Meanwhile, the acoustic coupling is also utilized to achieve improved pulse-echo performance with a novel PMUT

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structure. Next, the PMUT array optimizations based on different structural thicknesses will be studied theoretically and experimentally in the following chapter. The results show that a thin and densely packed array is the key to achieve high performance. Current cavity SOI wafer-based



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fabrication process is not good enough to achieve high fill-factor for high-frequency PMUT arrays. Thus, a novel surface micromachining process is proposed to fabricate high fill-factor PMUT arrays with improved performance.

With emerging micro-

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electromechanical system (MEMS) technology, MEMS ultrasonic transducers (MUTs) are demonstrated with the merits of smaller size, lighter weight, lower power consumption. Compared to conventional ultrasonic transducers, MUTs have better acoustic matching, CMOS

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compatibility, and array fabrications.

This dissertation focuses on high-performance MUTs, from the perspectives of driving mechanism, structure design, material, array design, fabrication process, sealing and housing, achieving higher transmitting pressure output, higher

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receiving sensitivity and wider bandwidth. First, this study investigates piezoelectric MUTs (PMUTs) and capacitive MUTs (CMUTs) to propose a novel hybrid MUT (HMUT) with the highest figure of merits (FoM) of MUTs. The HMUT is developed to remain the advantages

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of both MUTs for higher performance. For airborne applications, the HMUT is made by a PZT PMUT with large amplitude as transmitter (TX), and a capacitive CMUT with high sensitivity, wide bandwidth, and low bias, as receiver (RX). The airborne PMUT is fabricated by a single-crystal PZT thin

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film with a high piezoelectric coefficient ( $d_{31} = 15 \text{ C/m}^2$ ), enabling a high-pressure output of 108 dB SPL at 30 cm. The PZT PMUT with a dielectric constant ( $\epsilon_r = 308$ ) as RX, shows the sensitivity of 1.9 mV/Pa, resulting in high signal-to-noise ratio (SNR) in the pulse-echo

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experiment, demonstrating 5-meter round-trip detectable distance.

However, the PZT PMUT has generically high permittivity resulting in low receiving sensitivity, the narrow bandwidth (9%) due to high Q-factor, and TX/RX resonances mismatching, and mechanical nonlinearity. Here, we

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use a wide-bandwidth CMUT as a receiver to eliminate the resonances mismatching, and higher sensitivity can be achieved due to low permittivity ( $\epsilon_r$ ). The CMUT receiver, formed by a vented diaphragm and a small gap of 2  $\mu\text{m}$ , and CMUT with air damping is designed and optimized



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to have sensitivity of 14 mV/Pa, bias voltage of 5V, and fraction bandwidth of 150% from the mechanical characterization, resulting in 7X of sensitivity and 15X of bandwidth improvement compared to the single-crystal PZT PMUT. Moreover, the 3D printed housing of airborne MUTs is

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designed and implemented to protect the fragile structure and provide good acoustic impedance matching with air, enabling -1.4 dB acoustic loss from the housing, -2 dB SNR in pulse-echo measurement. For immersion MUTs, we utilized surface micromachining to developed MUTs, enabling high fill-

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factor MUT arrays with larger active areas to increase efficiency, and the MUT cavities can be sealed in vacuum for immersion applications. First, we demonstrated an AlN PMUT array with 80% fill-factor, and the PMUT cavities were sealed in vacuum. The explicit pressure model for MUT arrays with

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various fill-factor, is investigated from the experiments. Moreover, the structure enhancement is demonstrated using this process, resulting in higher PMUT pressure output. Compared to fully clamped PMUTs, the sloped PMUT with a 2.5X Q-factor (2.5X) can create 3X

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displacement by shaping the sacrificial layer. The corrugated PMUT is also implemented to demonstrate piston-like motions with an increasing active area, showing 3.2X volume velocity. In addition, the sealing technique with acoustic coupling layer is demonstrated to increase the

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bandwidth for immersion. Using surface micromachining, the immersion HMUTs is discussed and proposed to have the fully monolithic PMUT/CMUT integration with high performance.

Synthesis of KNN Thin Films Through Pulsed Laser Deposition for

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A Feasibility Study of Micromachined

Ultrasonic Transducers Functionalized

for Ethanol Detection

Fundamentals of Physical Acoustics

Transducers and Arrays for

Underwater Sound

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Properties of Lithium Niobate

**This book is a printed edition of the Special Issue "Imaging: Sensors and Technologies" that was published in Sensors**

**Emerging wide bandgap (WBG) semiconductors hold the potential to advance the global industry in**



**the same way that, more than 50 years ago, the invention of the silicon (Si) chip enabled the modern computer era. SiC- and GaN-based devices are starting to become more commercially available. Smaller, faster, and more efficient than their counterpart Si-**

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**based components, these WBG devices also offer greater expected reliability in tougher operating conditions. Furthermore, in this frame, a new class of microelectronic-grade semiconducting materials that have an even larger bandgap than the**

**previously established wide bandgap semiconductors, such as GaN and SiC, have been created, and are thus referred to as “ultra-wide bandgap” materials. These materials, which include AlGaN, AlN, diamond, Ga<sub>2</sub>O<sub>3</sub>, and BN, offer theoretically superior properties,**

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**including a higher critical breakdown field, higher temperature operation, and potentially higher radiation tolerance. These attributes, in turn, make it possible to use revolutionary new devices for extreme environments, such as**

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**high-efficiency power transistors, because of the improved Baliga figure of merit, ultra-high voltage pulsed power switches, high-efficiency UV-LEDs, and electronics. This Special Issue aims to collect high quality research papers, short**

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**communications, and review  
articles that focus on wide bandgap  
device design, fabrication, and  
advanced characterization. The  
Special Issue will also publish  
selected papers from the 43rd  
Workshop on Compound  
Semiconductor Devices and**

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**Integrated Circuits, held in France (WOCSDICE 2019), which brings together scientists and engineers working in the area of III–V, and other compound semiconductor devices and integrated circuits. In particular, the following topics are addressed: – GaN- and SiC-based**

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**devices for power and  
optoelectronic applications –  
Ga<sub>2</sub>O<sub>3</sub> substrate development, and  
Ga<sub>2</sub>O<sub>3</sub> thin film growth, doping, and  
devices – AlN-based emerging  
material and devices – BN epitaxial  
growth, characterization, and  
devices**



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**Piezoelectric Ceramics focuses on the relationship between piezoelectricity and ferroelectricity as they apply to ceramics, taking into consideration the properties of materials that are being used and possibly be used in the industries. Composed of 12 chapters, the book**

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**starts by tracing the history of piezoelectricity and how this affects ceramics. The different measurement techniques are discussed, including dielectric, ferroelectric, and piezoelectric measurements. The book proceeds by discussing Perovskite structure**

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**and barium titanate. Covered areas include electric field, piezoelectric properties, particle size effect, and dielectric strength. The properties, compositions, and reactions of various perovskites are discussed. Numerical analyses are presented in this regard. The book also offers**

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**interpretations of the experiments conducted. The discussions end with the processes involved in the manufacture and applications of piezoelectric ceramics. Concerns in manufacturing include calcination, grinding, mixing, electroding, firing, and quality control. Piezoelectric**

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**ceramics are applied in air transducers, instrument transducers, delay line transducers, underwater sound ultrasonic power, and wave filters. The book is important for readers interested in doing research on ceramics.**

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**Here the renowned editor Evgeny Katz has chosen contributions that cover a wide range of examples and issues in implantable bioelectronics, resulting in an excellent overview of the topic. The various implants covered include biosensoric and prosthetic devices,**

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**as well as neural and brain implants, while ethical issues, suitable materials, biocompatibility, and energy-harvesting devices are also discussed. A must-have for both newcomers and established researchers in this interdisciplinary field that connects scientists from**

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**chemistry, material science,  
biology, medicine, and electrical  
engineering.**

**Sensor Technologies for Civil  
Infrastructures**

**Introduction to Theory and Design  
of Sonar Transducers**

**Electroceramic-Based MEMS**



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**Piezoelectric Micro-machined  
Ultrasonic Transducers for Medical  
Imaging**

**2018 IEEE Sensors**

Ultrasonic methods have been very popular in nondestructive testing and characterization of materials. This book

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deals with both industrial ultrasound and medical ultrasound. The advantages of ultrasound include flexibility, low cost, in-line operation, and providing data in both signal and image formats for further analysis. The book devotes 11 chapters to ultrasonic methods. However,

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ultrasonic methods can be much less effective with some applications. So the book also has 14 chapters catering to other or advanced methods for nondestructive testing or material characterization. Topics like structural health monitoring, Terahertz methods, X-

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ray and thermography methods are presented. Besides different sensors for nondestructive testing, the book places much emphasis on signal/image processing and pattern recognition of the signals acquired.

This thesis explores optimization of a

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pulsed laser deposition process to synthesize high-quality potassium sodium niobate (KNN) thin films for use in piezoelectric micromachined ultrasonic transducers (pMUTs). The chemical and thermal interactions during calcination were investigated as well as

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sintering of a bulk KNN target from powder precursors. The implementation of two calcination processes at 750C and a sintering process at 1075C produced bulk KNN targets of high density. KNN thin films were deposited onto platinized silicon substrates through pulsed laser

deposition. The microstructure and phase purity were evaluated in the resultant films. Significant parameter variation was enacted onto the pulsed laser deposition process, based on parameter effects documented in literature and observation, to produce

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thin film characteristics that predict high piezoelectric performance. The platinized silicon substrate was aligned to the KNN target at varied target-to-substrate distance of 5.7 cm. The deposition ambient reached a base pressure of  $2.2 \cdot 10^{-7}$  Torr before being



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increased to a deposition ambient pressure of 400 mTorr. The substrate temperature was set to 550C and the pulse rate of the excimer laser was set to 5 Hz for a deposition duration of 6 minutes. The substrate was allowed to cool to room temperature at a cooling

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ambient pressure of 400 mTorr. The resultant pulsed laser deposition parameters yielded KNN thin films with high phase purity, but exhibited suboptimal microstructures featuring high surface roughness and porosity. Post-deposition thermal annealing

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processes were subsequently added to improve the thin film microstructure while retaining phase purity. Initial investigation into annealing optimization yielded phase pure polycrystalline thin films with improved microstructure at 700C for 5 minutes, suggesting that

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further optimization of the annealing process, along with investigation into KNN doping, could produce high quality KNN thin films suitable for implementation into pMUTs. The electrical characteristics of the resultant film were as follows: the remanent

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polarization ( $P_r$ ) was  $10.7 \text{ [}\mu\text{]C/cm}^2$ , the maximum polarization ( $P$ ) was  $12.7 \text{ [}\mu\text{]C/cm}^2$ , the dielectric constant ( $\epsilon_r$ ) was 605. The loss tangent ( $\tan\delta$ ) was 2.8%.

Handbook of Silicon Based MEMS  
Materials and Technologies, Third

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Edition is a comprehensive guide to MEMS materials, technologies, and manufacturing with a particular emphasis on silicon as the most important starting material used in MEMS. The book explains the fundamentals, properties (mechanical,

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electrostatic, optical, etc.), materials selection, preparation, modeling, manufacturing, processing, system integration, measurement, and materials characterization techniques of MEMS structures. The third edition of this book provides an important up-to-date

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overview of the current and emerging technologies in MEMS making it a key reference for MEMS professionals, engineers, and researchers alike, and at the same time an essential education material for undergraduate and graduate students. Provides comprehensive



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overview of leading-edge MEMS  
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methods of MEMS structures Reviews  
the current and future options for  
hermetic encapsulation and introduces  
how to utilize wafer level packaging and  
3D integration technologies for package  
cost reduction and performance  
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applications presenting several modern MEMS devices including inertial sensors, microphones, pressure sensors and micromirrors

This book contains 67 papers presented at ICTCA2001. It includes three keynote addresses surveying the frontier

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developments in computational and theoretical acoustics. The papers cover aero-, seismo- and ocean acoustics, as well as ultrasonics. Computational methods, numerical simulation, theoretical analysis and experimental results are emphasized by different

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ACOUSTICS Easy to read and

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understand, Fundamentals of Physical Acoustics fills a long-standing need for an acoustics text that challenges but does not overpower graduate students in engineering and physics.

Mathematical results and physical

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explanations go hand in hand, and a unique feature of the book is the balance it strikes between time-domain and frequency-domain presentations. Fundamentals of Physical Acoustics is intended for a two-semester, first-year graduate



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course, but is also suitable for advanced undergraduates.

Emphasis on plane waves in the first part of the book keeps the mathematics simple yet accommodates a broad range of topics: propagation, reflection and

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transmission, normal modes and simple waveguides for rectilinear geometries, horns, inhomogeneous media, and sound absorption and dispersion. The second part of the book is devoted to a more rigorous development of

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the wave equation, spherical and cylindrical waves (including the more advanced mathematics required), advanced waveguides, baffled piston radiation, diffraction (treated in the time domain), and arrays. Applications and examples

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are drawn from: \* Atmospheric  
acoustics \* Noise control \*

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chapter problems, Fundamentals of Physical Acoustics is also an excellent professional reference for engineers and scientists.

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survey of the field of IC design for Biological Sensing and Processing. The authors describe a multitude of applications that require custom CMOS IC design and highlight the techniques in analog and mixed-signal circuit design that



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potentially can cross boundaries  
and benefit the very wide  
community of bio-medical  
engineers.

This book introduces piezoelectric  
microelectromechanical (pMEMS)  
resonators to a broad audience by

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reviewing design techniques including use of finite element modeling, testing and qualification of resonators, and fabrication and large scale manufacturing techniques to help inspire future research and entrepreneurial

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activities in pMEMS. The authors discuss the most exciting developments in the area of materials and devices for the making of piezoelectric MEMS resonators, and offer direct examples of the technical

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challenges that need to be overcome in order to commercialize these types of devices. Some of the topics covered include: Widely-used piezoelectric materials, as well as materials in which there is

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emerging interest Principle of operation and design approaches for the making of flexural, contour-mode, thickness-mode, and shear-mode piezoelectric resonators, and examples of practical implementation of these devices

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Large scale manufacturing approaches, with a focus on the practical aspects associated with testing and qualification Examples of commercialization paths for piezoelectric MEMS resonators in the timing and the filter markets

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...and more! The authors present industry and academic perspectives, making this book ideal for engineers, graduate students, and researchers.

Fabrication-Technology and Applications

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## Data Collection Methods for Performance Assessment

High Efficient Piezoelectric  
Micromachined Ultrasonic  
Transducer Arrays

The impetus for the rapid  
development of thin film  
technology, relative to that of

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bulk materials, is its application to a variety of microelectronic products. Many of the characteristics of thin film ferroelectric materials are utilized in the development of these products - namely, their nonvolatile memory and

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piezoelectric, pyroelectric, and electro-optic properties. It is befitting, therefore, that the first of a set of three complementary books with the general title Integrated Ferroelectric Devices and Technologies focuses on the synthesis of thin film ferroelectric

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materials and their basic properties. Because it is a basic introduction to the chemistry, materials science, processing, and physics of the materials from which integrated ferroelectrics are made, newcomers to this field as well as veterans will find this

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book self-contained and invaluable in acquiring the diverse elements requisite to success in their work in this area. It is directed at electronic engineers and physicists as well as process and system engineers, ceramicists, and chemists

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involved in the research, design, development, manufacturing, and utilization of thin film ferroelectric materials.

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areas related to MEMS,

nanotechnology and molecular  
technology

Ultrasound transducers are used  
for many applications including  
medical imaging, non-destructive  
testing, obstruction detection,  
flow sensing, and gesture

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recognition. Piezoelectric micromachined ultrasound transducers (PMUTs) offer an attractive alternative to traditional bulk piezoelectric ultrasonic sensors, due to their compact size, increased transduction efficiency, and



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integrated array configuration. In this work, the development of aluminum nitride PMUTs for air coupled use is presented. The transducer consists of a circular composite diaphragm actuated using an aluminum nitride piezoelectric layer. An equivalent

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circuit model for a single clamped plate PMUTs has been developed and the design equations are presented and compared with finite element method simulations and measured values. The use of an acoustic resonator tube to boost the output pressure and

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increase the bandwidth of micro-scale transducers is demonstrated. The developed fabrication process for AlN PMUTs is presented. Clamped plate transducers operating from 100-300 kHz are characterized in the mechanical, electrical, and

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acoustic domains. The output pressure of the transducers at 5 cm is 90 mPa/V and the receive sensitivity is 0.8 mV/Pa. A flexurally suspended design with increased linearity and a piston-like mode shape is presented and the effect of perforations in the

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membrane surface determined. Finally, fabrication of PMUT arrays and sources of frequency mismatch, including geometric and the effects of residual stress are discussed. Through process improvements, across-die frequency matching of 1.5% is

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achieved which is well within the 6.6% fractional bandwidth of the transducer. The array acoustic performance is quantified and the on axis pressure is found to increase linearly with the number of excited elements and the beam-width of a 2D array is  $20^\circ$ .

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Mechanical Systems (MEMS)

Piezoelectric Ceramics

Design, Fabrication and

Applications

CMOS-MEMS

Synthesis, Properties and

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Applications

**This work focuses on air coupled piezoelectric ultrasonic transducers (PMUTs) for range finding and gesture recognition applications. Such**



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**applications require an  
array of identical PMUTs  
operating at center  
frequencies from 40-900  
kHz, a fractional  
bandwidth greater than 5%,  
and center frequency**

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**variation between PMUTs within the same array that does not exceed the fractional bandwidth. The first contribution of this work aims to reduce the in-wafer and in-die variation**

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**of the resonance frequency  
without degrading the PMUT  
performance. By designing  
a variable thickness  
diaphragm, a more robust  
diaphragm was designed  
while widening its**

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**bandwidth compared to flat solid plate with the same resonant frequency. The membranes are partially etched to remove mass, in a radial ribbed pattern that maintains the**

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**stiffness of the structure. This design achieves a 10 fold lower variation in the resonance frequency, while maintaining low quality factor for PMUTs at about**

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**200 kHz. The second contribution of this work concerns the design of PMUTs for higher frequencies.**

**Traditionally, air couple ultrasonic transducers**

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**operate at 40-200 kHz, in order to minimize loss in air. However, for some applications, the transmission range can be traded off in order to achieve better resolution.**

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**PMUTs at resonance  
frequencies from 200-900  
kHz were fabricated and  
characterized, and their  
loss in air was confirmed.  
The devices were  
fabricated using wafer-**



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**level bonding of a MEMS wafer to a CMOS wafer; therefore the acoustic effects due to the presence of the CMOS wafer were investigated. A back side cavity was required**

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**in order to prevent  
squeeze film damping  
between the membrane and  
the CMOS. Finally, a novel  
method to recycle the back-  
side acoustic pressure by  
redirecting it to the**

**front-side through  
concentric venting rings  
was demonstrated. The ring  
diameter determines the  
phase-shift between the  
sound emerging from the  
front-side port and the**

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ring, and can be adjusted to either amplify the far-field sound pressure level (SPL) or change the directivity of the output beam. Nine different ring designs were fabricated

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**and characterized, and a 4.5dB increase in on-axis SPL was measured. The methods used include analytic and numeric modeling of the piezo-acoustic systems as well**

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**as fabrication and  
characterization of  
devices. Multi-physics  
finite element models  
(FEM) were conducted using  
COMSOL and included the  
piezoelectric devices and**

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**the acoustic domains. Also a general dynamic model for a PMUT system that can evaluate performance in transmission and sensing was developed. It can also be adjusted for different**

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**boundary conditions and  
different diaphragm  
shapes. The model is not  
limited to linear  
coefficient, and therefore  
can also be used to study  
the non-linearity of the**



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**system. Then, devices with an aluminum nitride (AlN) piezo layer were fabricated both at the Marvell Nanofabrication Laboratory and in an industrial foundry.**

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**Frequency responses were studied in-air, using a laser Doppler vibrometer (LDV) and acoustic measurements were conducted using a B&K high frequency microphone.**

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**Combining both fundamental principles and real-life applications in a single volume, this book discusses the latest research results in ferroelectrics, including**

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**many new ferroelectric materials for the latest technologies, such as capacitors, transducers and memories. The first two chapters introduce dielectrics and**

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**microscopic materials properties, while the following chapter discusses pyroelectricity and piezoelectricity. The larger part of the text is devoted to**

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**ferroelectricity and  
ferroelectric ceramics,  
with not only their  
fundamentals but also  
applications discussed.  
The book concludes with a  
look at the future for**

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**laser printed materials  
and applications. With  
over 600 references to  
recent publications on  
piezoelectric and  
ferroelectric materials,  
this is an invaluable**

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**reference for physicists,  
materials scientists and  
engineers.**

**The chemical sensing  
system plays an important  
role in medical and  
environmental monitoring.**



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**Gases exhaled by humans include nitrogen, oxygen, water vapor, carbon dioxide and volatile organic compounds (VOCs). The VOCs are important and provide valuable**

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**information for non-invasive diagnosis. For instance, ethanol detection is beneficial for checking blood alcohol. In time blood alcohol level checking**

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**before checking can prevent a person from unsafe driving. Due to the extremely low concentration of the target gases, a gas sensor with high sensitivity,**

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**selectivity and low  
detection limit is  
required. There is a high  
demand for low cost, fast,  
accurate and easy-to-use  
self-check diagnosis  
devices. With low cost and**

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**high portability, micro-electromechanical systems (MEMS) sensors have been extensively studied for chemical sensing, which provide a cheap self-diagnosis solution.**

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**Capacitive Micromachined  
Ultrasonic Transducers  
(CMUTs) and Piezoelectric  
Micromachined Ultrasonic  
Transducer (PMUTs), which  
both work based on the  
mass-loading effect, are**

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**considered as the  
promising types of MEMS  
sensors for gas sensing.  
Since they are fabricated  
in a batch manner with the  
similar process of silicon-  
based integrated circuits,**

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**CMUTs and PMUTs are able to provide massive parallelism, easy integration with microelectronic circuits, and a higher quality factor. In this research,**



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**studied the feasibility of  
using PMUTs and CMUTs  
fabricated by our lab for  
ethanol detection through  
simulation and  
experiments. Models for  
are built via COMSOL for**

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**PMUT and CMUT  
respectively. The  
simulation results of a  
single sensing element  
demonstrated that both  
CMUTs and PMUTs show great  
potential for gas sensors.**

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**The chemical experiments through frequency response measurement exhibit that both the PMUTs and CMUTs are effective for ethanol detection based on the mass-loading effect. When**

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**the gas analyte is attached to the sensing layer, a higher resonance frequency of the transducer induces a higher frequency shift, which means the higher**

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**resonance frequency of  
transducer, the higher  
sensitivity of a gas  
sensor is and the lower  
concentration of ethanol  
can be detected.**

**Additionally, a CMUT array**

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**is also applied to ethanol detection. It provides a good preliminary study of the CMUTs functionalized with more sensing materials for chemical detection in future.**

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**This book introduces physical effects and fundamentals of piezoelectric sensors and actuators. It gives a comprehensive overview of piezoelectric materials**

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such as quartz crystals  
and polycrystalline  
ceramic materials.

Different modeling  
approaches and methods to  
precisely predict the  
behavior of piezoelectric



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**devices are described.**

**Furthermore, a simulation-based approach is detailed which enables the reliable characterization of sensor and actuator materials.**

**One focus of the book lies**

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on piezoelectric  
ultrasonic transducers. An  
optical approach is  
presented that allows the  
quantitative determination  
of the resulting sound  
fields. The book also

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**deals with various applications of piezoelectric sensors and actuators. In particular, the studied application areas are · process measurement technology, ·**

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**ultrasonic imaging, piezoelectric positioning systems and piezoelectric motors. The book addresses students, academic as well as industrial researchers and**

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**development engineers who  
are concerned with  
piezoelectric sensors and  
actuators.**

**Mechanics of Microsystems  
High Efficient  
Piezoelectric**

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Transducer Arrays  
Ultrasonic and Advanced  
Methods for Nondestructive  
Testing and Material  
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Handbook of Advanced**

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**Dielectric, Piezoelectric  
and Ferroelectric  
Materials**

**Air-coupled Aluminum  
Nitride Piezoelectric  
Micromachined Ultrasonic  
Transducers**

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***The book is focused on the use of functional oxide and nitride films to enlarge the application range of MEMS (microelectromechanical systems), including micro-***



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***sensors, micro-actuators,  
transducers, and  
electronic components for  
microwaves and optical  
communications systems.  
Applications, emerging  
applications, fabrication***

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***technology and functioning issues are presented and discussed. The book covers the following topics: Part A: Applications and devices with electroceramic-based MEMS:***

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***Chemical microsensors***

***Microactuators based on***

***thin films Micromachined***

***ultrasonic transducers***

***Thick-film piezoelectric***

***and magnetostrictive***

***devices Pyroelectric***

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***microsystems RF bulk  
acoustic wave resonators  
and filters High frequency  
tunable devices MEMS for  
optical functionality Part  
B: Materials, fabrication  
technology, and***

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***functionality: Ceramic  
thick films for MEMS  
Piezoelectric thin films  
for MEMS Materials and  
technology in thin films  
for tunable high frequency  
devices Permittivity,***

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*tunability and loss in*

*ferroelectrics for*

*reconfigurable high*

*frequency electronics*

*Microfabrication of*

*piezoelectric MEMS Nano*

*patterning methods for*

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***electroceramics Soft  
lithography emerging  
techniques The book is  
addressed to engineers,  
scientists and researchers  
of various disciplines,  
device engineers,***

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***materials engineers,  
chemists, physicists and  
microtechnologists who are  
working and/or interested  
in this fast growing and  
highly promising field.  
The publication of this***



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*book follows a Special Issue on electroceramic-based MEMS that was published in the Journal of Electroceramics at the beginning of 2004. The ten invited papers of that*

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***special issue were adapted  
by the authors into  
chapters of the present  
book and five additional  
chapters were added.  
The most comprehensive  
book on electroacoustic***

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***transducers and arrays for  
underwater sound Includes  
transducer modeling  
techniques and transducer  
designs that are currently  
in use Includes discussion  
and analysis of array***

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***interaction and nonlinear  
effects in transducers***

***Contains extensive data in  
figures and tables needed  
in transducer and array  
design Written at a level  
that will be useful to***

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***students as well as to  
practicing engineers and  
scientists***

***This book is a printed  
edition of the Special  
Issue "Piezoelectric MEMS"  
that was published in***

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## ***Micromachines***

***The book discusses the underlying physical principles of piezoelectric materials, important properties of ferroelectric/piezoelectric***

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*materials used in today's transducer technology, and the principles used in transducer design. It provides examples of a wide range of applications of such materials along*

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***with the appertaining  
rationales. With  
contributions from  
distinguished researchers,  
this is a comprehensive  
reference on all the  
pertinent aspects of***



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***Optimization of PZT Based***

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***Piezoelectric***

***Micromachined Ultrasound***

***Transducers for Air-***

***coupled Applications***

***Piezoelectric and Acoustic***

***Materials for Transducer***

***Applications***

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**CMOS Circuits for  
Biological Sensing and  
Processing**

*This comprehensive book covers recent developments in advanced dielectric, piezoelectric and ferroelectric materials. Dielectric materials such as ceramics are*

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*used to manufacture  
microelectronic devices.*

*Piezoelectric components have  
been used for many years in  
radioelectrics, time-keeping and,  
more recently, in microprocessor-  
based devices. Ferroelectric  
materials are widely used in*

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*various devices such as piezoelectric/electrostrictive transducers and actuators, pyroelectric infrared detectors, optical integrated circuits, optical data storage and display devices. The book is divided into eight parts under the general headings:*

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*High strain high performance piezo- and ferroelectric single crystals; Electric field-induced effects and domain engineering; Morphotropic phase boundary related phenomena; High power piezoelectric and microwave dielectric materials; Nanoscale*

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*piezo- and ferroelectrics; Piezo-  
and ferroelectric films; Novel  
processing and new materials;  
Novel properties of ferroelectrics  
and related materials. Each  
chapter looks at key recent  
research on these materials, their  
properties and potential*

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*applications. Advanced dielectric, piezoelectric and ferroelectric materials is an important reference tool for all those working in the area of electrical and electronic materials in general and dielectrics, piezoelectrics and ferroelectrics in*



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*particular. Covers the latest developments in advanced dielectric, piezoelectric and ferroelectric materials Includes topics such as high strain high performance piezo and ferroelectric single crystals Discusses novel processing and*

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*new materials, and novel properties of ferroelectrics and related materials*

*The major areas of activity in the development of MEMS and NEMS solicited and expected at this conference include but are not limited to materials, design,*

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*simulation, fabrication, assembly,  
packaging, experimental  
verification and analysis of micro  
and nanocomponents*

*Mechanics of Microsystems*

*Alberto Corigliano, Raffaele*

*Ardito, Claudia Comi, Attilio*

*Frangi, Aldo Ghisi and Stefano*

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*Mariani, Politecnico di Milano,*

*Italy A mechanical approach to*

*microsystems, covering*

*fundamental concepts including*

*MEMS design, modelling and*

*reliability Mechanics of*

*Microsystems takes a mechanical*

*approach to microsystems and*

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*covers fundamental concepts including MEMS design, modelling and reliability. The book examines the mechanical behaviour of microsystems from a 'design for reliability' point of view and includes examples of applications in industry.*

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*Mechanics of Microsystems is divided into two main parts. The first part recalls basic knowledge related to the microsystems behaviour and offers an overview on microsystems and fundamental design and modelling tools from a*

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*mechanical point of view,  
together with many practical  
examples of real microsystems.  
The second part covers the  
mechanical characterization of  
materials at the micro-scale and  
considers the most important  
reliability issues (fracture, fatigue,*

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*stiction, damping phenomena, etc) which are fundamental to fabricate a real working device.*

*Key features: Provides an overview of MEMS, with special focus on mechanical-based Microsystems and reliability issues. Includes examples of*



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*applications in industry.*

*Accompanied by a website  
hosting supplementary material.*

*The book provides essential  
reading for researchers and  
practitioners working with MEMS,  
as well as graduate students in  
mechanical, materials and*

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*electrical engineering.*

*Handbook of Silicon Based MEMS*

*Materials and Technologies*

*Piezoelectric Sensors and*

*Actuators*

*Beijing, China, 21-25 May 2001*

*Advanced Micro and*

*Nanosystems*

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*Principles and Applications*