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MICROMACHINED ULTRASOUND-BASED PROXIMITY SENSORS

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SPRINGER SCIENCE+BUSINESS MEDIA, LLC

ISBN 978-1-4613-7269-1 ISBN 978-1-4615-4997-0 (eBook)
DOI 10.1007/978-1-4615-4997-0

Library of Congress Cataloging-in-Publication Data

A C.I.P. Catalogue record for this book is available
from the Library of Congress.

Printed on acid-free paper.

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Foreword

Microsystems based on CMOS IC technology became feasible when CMOS-compatible micromachining and/or deposition were established in the last decade. Fabrication steps added to regular CMOS processes include, e. g., anisotropic etching of silicon or thin film deposition of "non-CMOS" materials. Preferably, such additional fabrication steps are performed after completion of the regular IC process as so-called post-processing or post-CMOS [see e.g. H. Baltes, O. Paul, O. Brand, "Micromachined thermally based sensors", Proc. IEEE, vol. 86, 1998, pp. 1660-1678].

This Ph.D. thesis describes the design, fabrication, and application of micromachined sensing elements capable of emitting and sensing ultrasonic waves. The devices are based on a stress-engineered silicon diaphragm structure, in which inherent stress in the multilayer diaphragm is exploited in order to increase sensitivity. The vibrating diaphragms are excited using thermal heaters, and sensed using piezoresistors. An important feature of the devices is that they have been designed to be able to be fabricated using a standard industrial CMOS process, thus obviating the need for extensive in-house fabrication capability for their realization. The thesis discusses the design of these sensing elements, their fabrication, their characterization, and their packaging, and then illustrates their use in several applications, including an ultrasound barrier and a proximity sensor.

In contrast to most other work from the Physical Electronics Laboratory of ETH Zurich, the combination of CMOS IC technology and anisotropic etching of silicon to release dielectric membranes was not sufficient here. While it is feasible to make integrated ultrasound transducers (transmitters and receivers) based on vibrating silicon dioxide membranes, their transducer efficiency is inferior to that of silicon membranes. Thus a way was found to produce silicon ultrasound transducers of high efficiency by combining CMOS technology with compatible electrochemical etching.

This thesis was part of a four-party collaboration which, besides the Physical Electronics Laboratory of ETH Zurich, involved the ETH's Integrated Systems Laboratory (Prof. Q. Huang) responsible for the circuit design, Austria Mikro Systeme International AG, Unterpremstätten, Austria (Prof. V. Kempe) running the CMOS process, and Baumer Electric AG, Frauenfeld, Switzerland (President H. Vietze) developing the resulting products.

Mark Hornung was the 20th Ph.D. student to complete his thesis under my supervision since I moved to ETH Zurich in 1988. His work is unique in that he extended our post-CMOS approach to silicon membranes and achieved complete packaged and tested microsystem prototypes exhibited at industrial trade shows. He now leads an industry-university collaboration project with ALPHA SENSORS, a spin-off company of our Laboratory.

Henry Baltes,
Zurich, Switzerland

Abstract

This thesis reports on a prototype of a packaged ultrasound barrier microsystem for object detection based on micromachined silicon transducer elements. Furthermore, the feasibility of a distance measuring system covering the distance range between 0.5cm up to 10cm is demonstrated. In both applications the transducer elements are excited at their fundamental resonance frequency to ensure maximum sensitivity. In this thesis four main topics are investigated: (a) optimization of the transducer elements with respect to the generated sound pressure, (b) long term stability of the resonators, (c) packaging, and (d) microsystem development and system characterization.

The ultrasound transducer elements were fabricated using industrial IC technology combined with standard silicon micromachining techniques. This approach allows a cost effective fabrication of the miniaturized resonators and the cointegration of the driving and read-out circuit. The transducer elements were fabricated using either an industrial pressure sensor process of *Micronas Semiconductor* or a CMOS process of *Austria Mikro Systeme International.*

The membrane resonators were optimized with respect to the generated sound pressure. Therefore, the resonator characteristics such as resonance frequency, vibration amplitude, and generated sound pressure were investigated for the different resonator geometries and the different fabrication processes. Additionally, finite element simulations of the device characteristics were performed to find the optimal membrane geometry. Square shaped membrane resonators with a side length of approximately 0.8mm generate the largest sound pressure at their resonance frequency of approxi-

mately 100kHz. The generated sound pressure is sufficient for measuring object distances up to 10cm.

Reliability and stability of the transducer elements were investigated to ensure the industrial applicability of the ultrasound microsystems. The long-term stability of the membrane resonators were tested under various environmental conditions like high temperature and humidity. Additional temperature cycles of packaged resonators were performed in order to investigate the stress fatigue. No failure of packaged transducers was observed even at a temperature and a relative humidity of 85°C and 85% RH, respectively, over more than two months. During operation, the resonance frequency initially slightly increased because the mechanical stress in the membrane changed. However, after a temperature dependent operation time, the resonance frequency stabilized. An activation energy E_a=0.37eV of the drift mechanism was measured. The frequency drift, however, does not influence the applicability of the membrane resonators in the ultrasound systems.

The packaging and housing, which mostly decide on success or failure of a microsystem, were intensively investigated. A low stress mounting of the transducer was developed which minimizes thermomechanical stress influences on the device. Furthermore, two different packaging approaches were investigated: in the first one, the generated ultrasound is emitted from the front side of the membrane, in the second the sound waves are emitted from the rear side through an opening in the substrate. The developed housing improves the sound generation efficiency of the transducer by increasing the impedance of the mechanical resonator. Additionally, a larger housing opening focuses the emitted sound waves and reduces the opening angle of the sound cone.

Based on the optimized transducer elements and the investigated packaging approaches, a packaged ultrasound barrier microsystem was developed. The micromachined resonators as well as the driving and read-out circuit were mounted on a common printed circuit board and encapsulated by a special housing. The circuit was developed and designed at the Integrated Systems Laboratory (IIS) of ETH Zurich. Furthermore, a proximity sensor system for measuring distances in the range from 0.5 to 10cm was developed in collaboration with the IIS. This system covers a distance range which is not measurable using conventional ultrasound proximity sensors. In this thesis three different, suitable measurement methods based on continuous ultrasound generation were investigated. Using the best method one can determine the object distance with an accuracy of better than 0.8mm over the whole distance range.

Acknowledgements

First of all I would like to thank my supervisor Prof. Dr. Henry Baltes for the great opportunity to do this work at the Physical Electronics Laboratory (PEL) at ETH Zurich. He understands to motivate people and to create a fruitful and enthusiastic atmosphere in his research group.

I wish to thank Prof. Dr. M. G. Allen for co-examining this thesis and for the critical proof-reading of the manuscript. I am also grateful to Prof. Dr. K. Hepp for his readiness to co-examine this thesis.

I am deeply indebted to Dr. Oliver Brand, my second co-examiner. He taught me the basics and a lot more about silicon micromachined resonators. His thesis created the basis for the ultrasound microsystems. He guided me during this thesis, also from Atlanta, and had always time to discuss technical and other problems.

I owe special thanks to Christoph Kuratli and Prof. Dr. Q. Huang for the circuit development and design. Without their help no ultrasound sensor system would exist.

I like to thank H. Vietze, C. Hafner, R. Mauch, C. Kluser (*Baumer Electric AG*, Frauenfeld) for initiating this work, for their support, and for many discussions.

Special thanks to Dr. Stephan Trautweiler and Thomas Müller for processing the membrane resonators at *Micronas Semiconductor*, Bevaix, and *Austria Mikro Systeme*

International, Unterpremstätten, respectively. I like to thank Rolf Frey for his efforts towards a packaging solution for the microtransducers.

I wish to thank Prof. Dr. O. Paul for many fruitful discussions and the theoretical models he developed. I very much like to thank Michael Schneider, Dr. Andreas Häberli, Stefan Koller, Andreas Koll and Dirk Lange for their stimulating collaboration and friendship.

It's a pleasure to remember the help of the PEL pioneers Dr. Thomas Boltshauser, Dr. Ruggero Castagnetti, and Dr. David Moser

I'm grateful to Erna Hug for very efficient administrative support and I owe thanks to Donat Scheiwiller, Igor Levak, Max Schlapfer, Peter Brühwiler and his crew, and Max Markwalder for technical assistance.

The entire staff of the Physical Electronics Laboratory has contributed to the success of this thesis. I received technical advice, stimulation and help from all my colleagues. It is pleasure to thank: Y. von Allmen, Dr. M. Bächtold, M. Brogle, Dr. D. Bolliger, Dr. F. Bose, Dr. J. Bühler, C. Cornila, M. Emmenegger, Dr. J. Funk, L. Glasl, C. Hagleitner, Dr. D. Jaeggi, Prof. Dr. J. G. Korvink, Dr. S. Linder, Dr. P. Malcovati, C. Maier, F. Mayer, M. Mayer, M. Metz, U. Münch, Dr. C. Riccobene, Dr. B. Rogge, Dr. F.-P. Steiner, R. Steiner, S. Tascini, N. Schneeberger, Dr. R. Vogt, M. von Arx, M. Wälti, V. Ziebart, and M. Zimmermann.

Last but not least, I wish to thank my parents, who always supported me in every respect.

The sensors presented in this work have been manufactured by *Micronas Semiconductors*, Switzerland, and *Austria Mikro Systeme International*, Austria.

This work has been supported by the Swiss Priority Program *MINAST* (*Micro- and Nano System Technology*), the *KTI* (*Kommission für Technologie und Innovation*) under the *M2S2* project (*Swiss Partnership for Micromechanics on Silicon*) and *Baumer Electric AG*, Frauenfeld, Switzerland.

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