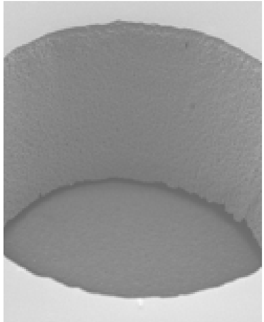

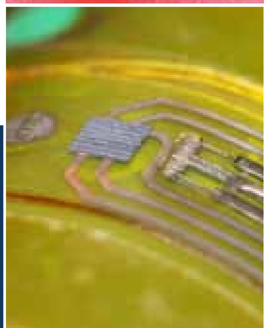

Micro sensor systems for aeronautical application in harsh environment

Martin Schwerter

Supervised by:

Prof. Dr. rer. nat.

Andreas Dietzel

Technische Universität Braunschweig

Institut für Mikrotechnik

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Von der Fakultät für Maschinenbau

der Technischen Universität Carolo-Wilhelmina zu Braunschweig

zur Erlangung der Würde

eines Doktor-Ingenieurs (Dr.-Ing.)

genehmigte Dissertation

von: Dipl.-Ing. Martin Schwerter
aus: Friesoythe

eingereicht am: 19.12.2017
mündliche Prüfung am: 05.04.2018

Gutachter: Prof. Dr. rer. nat. Andreas Dietzel
Univ.-Prof. Dr. rer. nat. Ulrich Schmid

2018

Schriftenreihe Mikrotechnik
herausgegeben von Prof. Dr. rer. nat. Andreas Dietzel

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Shaker Verlag
Aachen 2018

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Braunschweig, Techn. Univ., Diss., 2018

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Printed in Germany.

ISBN 978-3-8440-5948-9
ISSN 2568-2040

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

Preface and acknowledgment

The work described in this thesis was carried out while I was research assistant at the Institute of Microtechnology (IMT) at the Technische Universität Braunschweig from February 2013 to December 2017. Funding was provided by the German Research Foundation (DFG) within the framework of the collaborative research center (CRC) 880 "Fundamentals of high-lift for future civil aircraft" where I was involved in the subproject B2 "Adaptive systems for flow control".

I owe thanks for the successful accomplishment of my project to many people. Special thanks go to my supervisor Andreas Dietzel. He not only provided the necessary facilities and resources to ensure that my research could be successfully performed; he was also always available for ideas as well as constructive and trusting discussions. I would also like to thank Monika Leester-Schädel for her valuable and friendly support during this research.

Furthermore, I would like to thank Ulrich Schmid and the team of the Institute for Sensor and Actuator Systems at the Technische Universität Wien for a very pleasant and interesting research stay.

I owe not only a whole series of ideas, but also many enjoyable hours during work at the IMT and also in private life to my colleagues, especially to the Eugen Kochs (both I and II), David Metz, Peer Erfle and Ingmar Leber. I would like to thank Jan Niklas Haus in particular for the critical review of my work. Thanks are also to the technical staff and trainees for the good maintenance of cleanroom operation and technical devices, and the production of microsystems. In particular, Anke Vierheller supported me a lot during the fabrication of my devices in the cleanroom. I would also like to thank my former students, especially Daniel Gräbner, for many good ideas they have provided during their student work.

Thanks are also to the alumni Tobias Beutel and Nelson Ferreira for their good hints and advice. I would also like to thank Daniel Klaas for the inspiring discussions on science and beyond.

My personal thanks go to my parents Elisabeth and Andreas, my brother Johannes, as well as Olga and my niece Anna for their great support during the doctoral period.

Abstract

Mankind's increasing desire for mobility has led to growing air traffic which is associated with increasing burdens on the population and the environment. Technical solutions can be an appropriate way to considerably reduce noise and pollutant emissions. A high-lift system can reduce flow-induced noise, since it provides sufficient lift for a safe flight even at lower flight speeds, thereby reducing noise near airports.

Actively controlled high-lift systems require local sensing of flow and pressure as feedback. Miniaturized sensors with smallest space requirements can be integrated evenly distributed in airfoils and provide local information on the fluid pressure and wall shear stress. However, the harsh conditions during high-lift experiments in a water tunnel as well as in future aircraft operation require a special protection.

For wall shear stress measurements, a fully flexible, 7 µm thin hot-film sensor based on polyimide foil substrate is adapted for the application in water. For pressure measurements, a surface passive sensor concept leading to a flip-chip mountable piezoresistive sensor with a flat and waterproof surface is developed. This completely new design is realized using innovative manufacturing processes such as femtosecond laser ablation of glass. Through novel concepts of through glass vias and bonding a considerable miniaturization compared to pre-existing concepts is achieved (lateral dimension of $2.2 \times 2.2\ mm^2$, thickness of only 0.22 mm).

Both types of sensors are combined to form an integrated sensor system including amplification electronics to be used in water. It enables the measurement of pressure and wall shear stress at nearly the same location. Furthermore, a flexible, foil-like sensor system for combined pressure and wall shear stress measurements is manufactured and investigated. It is tested for the application on curved surfaces down to 20 mm bending radius. The sensors show similar response characteristics in bent and unbent state.

Keywords: Pressure sensor, hot-film sensor, sensor system, harsh environment, flip-chip mounting

Kurzfassung

Der stetig wachsende Wunsch nach Mobilität führte zu einem Anstieg des Luftverkehrs, einhergehend mit einer steigenden Belastung von Umwelt und Bevölkerung. Technische Lösungen können geeignet sein, um Lärm und Emissionen deutlich zu reduzieren. Ein Hochauftriebssystem kann den strömungsbedingten Lärm reduzieren, weil es ausreichend Auftrieb erzeugt für einen sicheren Flug auch bei niedrigen Fluggeschwindigkeiten, wodurch eine Reduzierung des Lärms in Flughafennähe möglich ist.

Aktiv geregelte Hochauftriebssysteme erfordern das lokale Messen der Strömung und des Druckes. Miniaturisierte Sensoren mit geringstem Platzbedarf können hierzu gleichmäßig verteilt in Tragflächen integriert werden und erfassen lokal Informationen zum Druck und der Wandschubspannung der Strömung. Die harschen Bedingungen in Hochauftriebsexperimenten im Wasserkanal sowie während des zukünftigen Flugbetriebs erfordern einen speziellen Schutz.

Zur Wandschubspannungsmessung wird ein vollflexibler, 7 µm dünner Heißfilmsensor auf Polyimidfolie zur Verwendung unter Wasser adaptiert. Zur Druckmessung wird ein oberflächenpassives Sensorkonzept in Form eines Flip-Chip montierbaren, piezoresistiven Drucksensors mit einer glatten, wasserfesten Oberfläche entwickelt. Dieses komplett neue Design wird unter Verwendung innovativer Fertigungsverfahren wie der Femtosekundenlaser-Ablation von Glas realisiert. Durch neue Konzepte wie der Glas-Durchkontaktierung und des Bondens wird eine beträchtliche Miniaturisierung im Vergleich zum vorhandenen Konzept erreicht (laterale Abmessung 2.2×2.2 mm², Dicke von nur 0.22 mm).

Beide Sensortypen werden zu einem integrierten Sensorsystem mit Verstärkerelektronik zur Verwendung unter Wasser kombiniert. Es ermöglicht die Messung von Druck und Wandschubspannung an nahezu dem gleichen Ort. Ferner wird ein flexibles, folienartiges Sensorsystem zur direkten Montage auf gekrümmte Oberflächen hergestellt und untersucht. Es kann auf gekrümmte Oberflächen mit einem Biegeradius von nur 20 mm aufgebracht werden. Der Sensor zeigt ein vergleichbares Antwortverhalten im gebogenen und ungebogenen Fall.

Schlagwörter: Drucksensor, Heißfilmsensor, Sensorsystem, Harsh Environment, Flip-Chip Montage

Contents

List of symbols and abbreviations

List of symbols

Symbol (latin)	Unit	Explanation
$A_{hot-film}$	µm²	Hot-film sensor surface
C	$mol \cdot m^{-3}$	Concentration
c	$J \cdot K^{-1}$	Heat capacity
D	$m^2 \cdot s^{-1}$	Diffusion coefficient
d	µm	Diffusion depth
d_p	µm	Particle diameter
E	µJ	Pulse energy
f	kHz	Pulse repetition frequency
g	$m \cdot s^{-2}$	Gravity
h	$W \cdot m^{-2} \cdot K^{-1}$	Heat transfer coefficient
h_f	m	Fluid height
h_{mem}	µm	Membrane stroke
I	A	Current
J	$mol \cdot m^{-2} \cdot s^{-1}$	Diffusion flux
K	-	Piezoresistive factor
l	m	Length
m	kg	Mass
P	W	Power
p	$Pa = N \cdot m^{-2}$	Pressure
p_0	$Pa = N \cdot m^{-2}$	Ambient pressure
p_{fluid}	$Pa = N \cdot m^{-2}$	Pressure of a fluid to be measured

P_L	W	Average laser power
p_{ref}	$Pa = N \cdot m^{-2}$	Enclosed reference pressure
p_s	$Pa = N \cdot m^{-2}$	Static pressure
p_w	$Pa = N \cdot m^{-2}$	Water pressure
p_{xy} (p_{00}, p_{01}…)	-	Calibration coefficient
$\dot{Q}$	W	Heat flow
R	Ω	Resistance
R^2	-	Coefficient of determination
r	m	Radius
R_l	$\Omega \cdot \mu m^{-1}$	Resistance per length
R_s	Ω	Sheet resistance
T	K	Temperature
T_S	K	Hot-film sensor temperature
T_{fluid}	K	Fluid temperature
T_{ref}	K	Reference temperature
t	s	Time
u	$m \cdot s^{-1}$	Flow velocity
U	V	Voltage
U_B	V	Hot-film bridge voltage
V_{cc}	V	Supply voltage
w	µm	Diffusion mask opening width
w_A	µm	Actual diffusion width
w_k	µm	Width of under-doped area
x	m	Location

Symbol (greek)	Unit	Explanation
α	K^{-1}	Linear temp. coefficient of resistance
β	K^{-2}	Quad. temp. coefficient of resistance
ε	-	Relative elongation
ϑ	°C	Temperature
μ	$kg \cdot m^{-1} \cdot s^{-1}$	Dynamic viscosity
ρ	$kg \cdot m^{-3}$	Density
σ	$Pa = N \cdot m^{-2}$	Mechanical normal stress
τ	$Pa = N \cdot m^{-2}$	Wall shear stress

List of abbreviations

Abbreviation	Explanation
Au	Gold
Bi	Bismuth
CCA	Constant current anemometry
CF_4	Tetrafluoromethane
CIG-MI	“cavity in glass” with metallic interface
CIG-NMI	“cavity in glass” with non-metallic interface
CMOS	Complementary metal-oxide-semiconductor
CO_2	Carbon dioxide
CRC	Collaborative research center
CTA	Constant temperature anemometry
EEPROM	Electrically erasable programmable read-only memory
FEM	Finite element method
FFC	Flexible flat cable

FPGA	Field programmable gate array
fs	Femtosecond (= 10^{-15} s)
HF	Hydrofluoric acid
IC	Integrated circuit
IMT	Institute of Microtechnology
KOH	Potassium hydroxide solution
MEMS	Micro-electro-mechanical-system
MOSFET	Metal oxide semiconductor field-effect transistor
n	Negative
Na	Sodium
O_2	Oxygen
p	Positive
PC	Personal computer
PCB	Printed circuit board
PDMS	Polydimethylsiloxan
PECVD	Plasma enhanced chemical vapor deposition
PGA	Programmable gain amplifier
PIV	Particle image velocimetry
PVDF	Polyvinylidene fluoride
SD	Standard deviation
SF_6	Sulfur hexafluoride
Si	Silicon
Si_3N_4	Silicon nitride
SiO_2	Silicon oxide
SLID	Solid-liquid interdiffusion

Sn	Tin
SOI	Silicon-on-insulator
SPI	Serial peripheral interface
SU-8	Negative photoresist by Microchem Corp.
TCR	(Linear) temperature coefficient of resistance
UART	Universal asynchronous receiver/transmitter
USB	Universal serial bus
VGA	Video graphics array
Yb:KGW	Ytterbium-doped potassium gadolinium tungstate