

Berichte aus der Medizintechnik

Marcin Meyer

**A Flexible and Stretchable Wireless
Health Monitoring Sensor Platform
Connected to a Mobile Device**

Shaker Verlag
Aachen 2015

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.: Dresden, Techn. Univ., Diss., 2015

Copyright Shaker Verlag 2015

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-3989-4

ISSN 1431-1836

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



**TECHNISCHE
UNIVERSITÄT
DRESDEN**

A Flexible and Stretchable Wireless Health Monitoring Sensor Platform Connected to a Mobile Device

Dissertation

zur Erlangung des akademischen Grades

Doktoringenieur (Dr.-Ing.)

vorgelegt von

Marcin Meyer

geboren am 1. September 1986 in Złotów

Technische Universität Dresden

Fakultät Maschinenwesen

Institut für Werkstoffwissenschaft

Lehrstuhl für Materialwissenschaft und Nanotechnik

1. Gutachter: Prof. Dr. Gianarelio Cuniberti, TU Dresden, Deutschland
2. Gutachter: Prof. Dr. Hans-Georg Braun, IPF Dresden, Deutschland
3. Gutachter: Prof. John A. Rogers, UIUC, IL, USA

Tag der Einreichung: 07.06.2015

Tag der Verteidigung: 17.07.2015

Abstract

In this thesis, a flexible and stretchable wireless health monitoring sensor platform connected to a mobile device was designed from scratch, built and patented.

The platform consists of a wireless, flexible and stretchable electronic plaster located on the skin and an RFID-reader in the form of a micro-USB-stick operated with a mobile application. The wireless tag is made of a thin layer of metal and electronic components which are encapsulated in a stretchable and flexible thin layer of a transparent, biocompatible polymer. The electronic plaster can be reversibly stretched up to 50% and is lightweight, waterproof, biocompatible and adhesive, so that it can be easily placed on human skin for up to 30 days. Moreover, because of its gas permeability and simultaneous bacteria impenetrability the electronic plaster is a perfect breathable wound dressing. It is important to note that almost any sensor in which resistance changes are related to a change in a measured value can be implemented in this electronic plaster. The system was successfully tested with a temperature sensor and a flexible high-performance silicon nanowire based biosensor for early detection of avian influenza virus DNA sequences. The developed and patented mobile RFID-receiver wirelessly powers the plaster and collects medical signals. These signals are then amplified, filtered, and recalculated in a digital signal processor. The collected data is shown in a patient-friendly format on the display of a mobile Android device such as a smartphone or tablet. The developed app makes it possible to evaluate and save data, as well as send it to a physician if necessary.

With its modular design, the platform supports monitoring of vital parameters and provides a reliable, comfortable, and economical solution for hospitals, nursing homes, as well as everyday users.

Kurzfassung

Im Rahmen der vorliegenden Doktorarbeit wurde eine App-gesteuerte, dehnbare und flexible drahtlose epidermische Sensorplattform zur Gesundheitsüberwachung von Grund auf entworfen, implementiert und patentiert.

Die Plattform besteht aus einem mit medizinischen Sensoren ausgestatteten elektronischen Heftpflaster, einem portablen RFID-Empfänger und einer Applikation für mobile Endgeräte. Das dehnbare Heftpflaster mit der Möglichkeit zur drahtlosen Datenübertragung besteht aus dünnen Metallschichten, die als Zwischenverbindungen dienen und elektronischen Komponenten, die in einer dehnbaren und flexiblen dünnen Schicht bestehend aus einem transparenten und biokompatiblen Polymer verkapselt sind. Das elektronische Heftpflaster kann um bis zu 50% elastisch gedehnt werden und ist zudem leicht, wasserfest, biokompatibel und adhäsiv, so dass es für einen Zeitraum von bis zu 30 Tagen auf der Haut der Patienten platziert werden kann. Darüber hinaus ist es aufgrund seiner Gasdurchlässigkeit bei gleichzeitiger Undurchdringlichkeit für Bakterien eine perfekte atmungsaktive Wundauflage. Es ist wichtig zu erwähnen, dass fast jeder Sensor, bei dem die Änderung des elektrischen Widerstandes proportional zur Änderung der Messwerte ist, in das elektronische Heftpflaster implementiert werden kann. Während des Promotionsprojektes wurde das System erfolgreich mit einem Temperatursensor und einem flexiblen Hochleistungsbiosensor basierend auf Silizium-Nanodrähten, der zur Früherkennung von den Vogelgrippe-Virus-DNA-Sequenzen eingesetzt werden kann, realisiert und eingehend untersucht. Der parallel entwickelte und patentierte mobile RFID-Empfänger verbindet das Heftpflaster drahtlos und sammelt die medizinischen Signale. Diese Signale werden anschließend verstärkt, gefiltert und im digitalen Signalprozessor weiterverarbeitet. Die gesammelten Daten werden in einer patientenfreundlichen Weise auf dem Display eines mobilen Android-Gerätes, wie einem Smartphone oder Tablet- präsentiert. Die entwickelte App ermöglicht es zudem, die so erfassten Daten zu bewerten und zu speichern, als auch wenn nötig an einen Arzt weiterzuleiten.

Mit dem hier präsentierten modularen Aufbau unterstützt die entwickelte Sensorplattform die Überwachung von lebenswichtigen Gesundheitsparametern. Dieser Ansatz bietet eine zuverlässige komfortable und wirtschaftliche Lösung für Pflegeheime, Krankenhäuser und private Nutzer.

Content

Abstract	III
Kurzfassung	V
Content	VII
Figures	XI
Tables	XV
Abbreviations.....	XVII
I. Introduction	1
I.I Motivation	1
I.II Scope of the Thesis	5
II. State of the Art.....	7
II.I Stretchable and wearable devices	7
II.I.1 Basic requirements of the material	9
II.I.2 Wavy structural configuration	11
II.I.3 Stretchable interconnections	13
II.I.4 Energy sources	18
II.II Wireless data transmission	21
II.III Wound monitoring	23
II.IV Mobile medical applications	27
III. Materials and Methods	29
III.I Thin metal layers	29
III.II Lithography	30
III.II.1 Laser lithography	30

III.II.2	UV-Lithography	31
III.III	Etching	32
III.III.1	Wet etching	32
III.III.2	Reactive Ion Etching	33
III.IV	Polymers	34
III.V	Human fibroblasts culturing	36
III.VI	RFID	38
III.VII	Others	41
IV.	Stretchable wireless tag	42
IV.I	Rigid prototype	42
IV.II	Flexible circuit design	45
IV.II.1	Interconnections	45
IV.II.1	Antenna	47
IV.III	Final stretchable device	51
V.	RFID reader	56
V.I	Prototype for PC	57
V.II	RFID-reader for mobile devices	60
VI.	Mobile application.....	67
VII.	Sensing applications	68
VII.I	Temperature sensing	68
VII.II	DNA sensing	73
VII.III	Cells impedance measurements	74
VII.IV	Skin modulus measurement	77

VIII. Closing remarks	79
VIII.I Conclusion	79
VIII.I.1 Functionality and cost	81
VIII.II Outlook	82
Scientific Output.....	85
Acknowledgements	87
References	93

Figures

Figure 1. Demographic changes in Germany.	1
Figure 2. The idea of a mobile medical sensor platform.	3
Figure 3. Multifunctional EES on the skin[13].	7
Figure 4. Illustration of a thin large-area active-matrix sensor[20].	8
Figure 5. Young's modulus for various substances[22].	10
Figure 6. Getting stretchable Si devices on elastic substrates by buckling process[23].	11
Figure 7. Scanning electron microscope image of wavy silicon ribbons[23].	12
Figure 8. Stretching test of wavy silicone p–n diode ribbons on a PDMS substrate[23].	12
Figure 9. Architecture of an elastic electronic surface[22].	13
Figure 10. A schematic representation of horseshoe interconnections[23].	15
Figure 11. The fabrication process of 3D metal interconnections[30].	16
Figure 12. Flexible metallic wires embedded in PDMS wrapped around a glass capillary[30]	16
Figure 13. Cross-sectional optical microscopy images and FEM of PDMS [37].	18
Figure 14. Production process of the GaAs photovoltaic cells[37].	19
Figure 15. The photovoltaic properties of the organic solar cell[38].	20
Figure 16. Key RFID chip.	22
Figure 17. The change of the impedance proportional to the amount of cells on the gold electrodes[45].	23
Figure 18. ThermoDock® [63].	28
Figure 19. Worldwide smartphone sales to end users by operating system [58].	28

Figure 20. Leybold UNIVEX 300 vacuum evaporation system.	29
Figure 21. Laser lithography DWL66FS, Heidelberg Instruments.	30
Figure 22. UV-lithography, MJB4, Karl Suss Microtec.	31
Figure 23. Plasma RIE system-Pico 300W, 13.56MHz, Diener electronic GmbH.	33
Figure 24. k_1 for the cure reaction at 80°C as a function of the thickness of the silicone coating on four different types of substrates [70].	35
Figure 25. 16 E-Plate and culture flask with a medium consisting human cell line Hs27.	37
Figure 26. Set-up for cell impedance measurements.	37
Figure 27. 16 E-Plate, ACEA Biosciences.	38
Figure 28. The electronic circuit of the RFID sensor tag.	42
Figure 29. Design of the wireless tag PCB.	44
Figure 30. Rigid wireless tag with a temperature sensor.	44
Figure 31. Wireless tag interconnections using second order serpentines.	45
Figure 32. Symmetric distribution of the components connected by first order serpentines.	46
Figure 33. Cross-section of the device.	46
Figure 34. The interconnections stretched up to 60%.	47
Figure 35. Antenna design with a horseshoe shape.	48
Figure 36. The relation between resistance and copper thickness.	49
Figure 37. Various serpentines for antenna design.	50
Figure 38. Stretching test for various types of serpentines I, II and III.	50
Figure 39. Following layers of the wireless sensor tag.	51
Figure 40. Devices with three various types of antennas.	52
Figure 41. Elongation of the whole circuit.	53

Figure 42. The wireless tag located on the skin.	53
Figure 43. Deformation of the wireless sensor tag.	54
Figure 44. The wireless sensor tag under water.	55
Figure 45. One of the main differences between standard RFID readers and the one described below.	56
Figure 46. Data transmission within the platform.	57
Figure 47. RFID-reader for PC.	58
Figure 48. The correlation between distance and power transmission.	59
Figure 49. Screenshot of the PC application.	59
Figure 50. Infineon XMC4500 Relax Kit.	60
Figure 51. Design (left) and real (right) PCB of the RFID-reader.	61
Figure 52. Working schematic of the DSP.	62
Figure 53. Schematic of the signal collected from the wireless sensor tag.	63
Figure 54. Different results for different signal shifts (or displacement).	64
Figure 55. Autocorrelation function.	65
Figure 56. Compact RFID reader for mobile devices.	66
Figure 57. Shot screen of the mobile app for temperature measurement.	67
Figure 58. Calibration of the temperature sensor.	68
Figure 59. Calibration set up.	69
Figure 60. Unfiltered signals by 25°C and 60°C for various antennas.	70
Figure 61. The filtered signals by 25°C and 60°C for various antennas.	70
Figure 62. Relation between the frequency and the temperature value for various antennas.	71
Figure 63. Calibration of the DNA sensor connected to the wireless tag.	73
Figure 64. Scratched surface (left), scratched surface after 3 days (right).	74

Figure 65. Qualitative measurement of the relation between cell volume and the impedance signal [117].	75
Figure 66. The flexible wireless sensor tag located on the open wound.	76
Figure 67. Piezoelectric Young modulus sensor placed on the artificial skin.	77
Figure 68. Health monitoring sensor platform.	79
Figure 69. The wireless sensor tag used for temperature measurement in an aquarium.	81
Figure 70. Potential application of a Flexible and Stretchable Wireless Mobile Health Monitoring Sensor Platform for temperature measurement.	83
Figure 71. Selected steps of the stretchable sensor tag production.	104

Tables

Table 1. RFID classification according to the transmission frequency range	23
Table 2. Etching time and power level for various thicknesses of the PI layer	34
Table 3. Technical data about the used polymers[65]–[67]	34
Table 4. Patents about RFID readers with DSP	39
Table 5. Dependence between used metal and antenna resistivity	48
Table 6. Temperature measurements with the sensor platform	72

Abbreviations

App – a mobile application

Cps – centipoise, the unit of dynamic viscosity in the centimeter gram second system of units

DSP – digital signal processor

ECM – extracellular matrix

EGF – epidermal growth factor

FEM – finite element method

FGF – fibroblast growth factor

IL-1 β – interleukin one beta

IR – infrared

LIGA – Lithography, Electroplating and Molding

MMP – matrix-metalloproteinase

MWCNT – multiwall carbon nanotube

PC – personal computer

PCB – printed circuit board

PDGF – platelet-derived growth factor

PDMS – polydimethylsiloxane

PEDOT – poly (3,4-ethylenedioxythiophene): p-tosylate

PI – polyimide

PMMA – polymethyl methacrylate

PR – photoresist

PSS – poly(styrenesulfonate)

PUR – polyurethane elastomer

RFID – radio-frequency identification

RIE – reactive ion etching

SEM – Scanning Electron Microscope

SMD – surface mounted device

TGF- β – transforming growth factor beta

TNF- α – tumor necrosis factor alpha

TU Dresden – Dresden University of Technology